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An Evaluation of Existing Tire Pressure Monitoring Systems

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16. Abstract

In the TREAD Act of November 1, 2000, Congress required the National Highway Traffic Safety Administration (NHTSA) to develop a rule requiring all new light vehicles to be equipped with a warning system to indicate to the operator when a tire is significantly underinflated. In response to this requirement, NHTSA undertook an evaluation of existing OEM and aftermarket tire pressure monitoring systems. In this evaluation NHTSA determined the capabilities of existing technologies and the methods of warning the driver that were under consideration by system manufacturers. Based on this evaluation, NHTSA will determine the minimum system performance criteria that are technically feasible and provide the most useful information to the driver for preventing unsafe conditions.

Through its testing, NHTSA found that systems that use sensors to directly measure tire pressure (pressure-sensor based systems) were better able to detect underinflation, had more consistent warning thresholds, and were quicker to provide underinflation warnings than the systems that infer tire pressure from monitoring wheel speeds (wheel-speed based systems). Training the systems presented at least some level of problem for both system types. Wheel-speed based systems were found to be easier to maintain since there are no battery life concerns and the fact that sensors are not exposed to tire mounting and roadway hazards.

An examination of driver interfaces for existing TPMS showed significant variation in methods of visual warning presentation. Visual displays were frequently difficult to see or comprehend, or both. The variation in visual warning presentation demonstrated the need for standardization of the visual warnings of tire underinflation to avoid driver confusion. Icon comprehension testing, which examined the ability of two ISO icons and 13 alternative icons to communicate the message of low tire pressure, showed that the ISO icons performed worse than all of the other icons. Six of the alternative icons received 100 percent comprehension. One of the icons was identified as most likely to be successful as an indicator of significant underinflation.

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CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.54	centimeters	cm
ft	feet	30	centimeters	cm
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
		PRESSURE		
psi	pounds per $inch^2$	0.07	bar	bar
psi	pounds per $inch^2$	6.89	kilopascals	kPa
		VELOCITY		
mph	miles per hour	1.61	kilometers per hour	km/h
		ACCELERATION		
ft/s^2	feet per $second^2$	0.30	meters per $second^2$	m/s^2
		TEMPERATURE (exact)		
°F	Fahrenheit	5/9 (Celsius) - 32°C	Celsius	°C

Approximate Conversions to English Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
km^2	square kilometers	0.4	square miles	mi^2
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
		PRESSURE		
bar	bar	14.50	pounds per $inch^2$	psi
kPa	kilopascals	0.145	pounds per $inch^2$	psi
		VELOCITY		
km/h	kilometers per hour	0.62	miles per hour	mph
		ACCELERATION		
m/s^2	meters per $second^2$	3.28	feet per $second^2$	ft/s^2
		TEMPERATURE (exact)		
°C	Celsius	9/5 (Celsius) + 32°F	Fahrenheit	°F

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EXECUTIVE SUMMARY

In support of a TREAD Act mandated rulemaking effort, NHTSA studied ten existing, light vehicle, Tire Pressure Monitoring Systems (TPMS). The TPMS were classified as two types, Wheel-Speed Based - WSB (often referred to as "indirect") and Pressure-Sensor Based - PSB (often referred to as "direct"). Wheel-Speed Based TPMS infer tire pressures using the vehicle's ABS hardware, specifically the wheel speed sensors, to measure tire-to-tire differences in rotational velocities. Pressure-Sensor Based TPMS directly measure tire pressures with pressure sensors mounted either in each tire or on each wheel.

TPMS EVALUATION METHOD

Four vehicles equipped with Wheel-Speed Based TPMS were studied. For all of these vehicles, the vehicle manufacturer installed the TPMS as original equipment. For each vehicle equipped with a WSB TPMS, the goals of the testing were to determine:

1. The accuracy of the TPMS
2. The repeatability of the TPMS
3. When the TPMS issues a warning to the driver
4. How the TPMS issues a warning to the driver
5. How to reset/train the TPMS when tires are replaced or rotated

WSB TPMS cannot treat the tires independently. Therefore, to determine the sensing capabilities of each system, each vehicle was tested with multiple combinations of tires being deflated.

Six Pressure-Sensor Based TPMS were studied. One was manufacturer-installed as original equipment, while the other five were installed on test vehicles by the VRTC. In addition to the goals listed above (for WSB systems), PSB TPMS were also examined with the following additional goals in mind:

1. How the TPMS handles temperature effects
2. What the TPMS does when the system fails

This study also examined the recognizability of underinflated tire warnings that were given to drivers, i.e., the human factors of the warnings. The visual and auditory displays used to present tire pressure warning information were examined. Comprehension Tests were conducted to determine the recognizability of two ISO tire pressure icons and 13 alternative tire pressure icons.

RESULTS

Wheel-Speed Based System Results

Four WSB systems installed as original equipment on 2000 or2001 vehicles were evaluated. Testing showed that all of the WSB systems would warn of a single tire being significantly underinflated (50 percent low) on a winding road course. However, on the 7.5 mile oval test track, which requires little turning input, only three of the four systems could detect tire pressure as low as 14 psi. The WSB systems also did not warn of two tires equally underinflated on the same side of the vehicle or on the same axle. Three of four systems warned of two underinflated tires in diagonal positions. All of the systems warned of three tires equally underinflated. None of the four WSB systems were able to warn of all four tires equally underinflated. The observed warning capabilities of these systems corresponded to the theoretical limitations of the sensing algorithm documented in this report.

The warning thresholds of the WSB systems were experimentally determined by slowly leaking out air, to a minimum of 14 psi, while driving at 60 mph on the 7 ½ mile oval test track. The percent drop in pressure was calculated per axle and displayed in the following table. Overall, the warning thresholds ranged from 8 percent low to 46 percent low, with one system giving no warning at all on the oval track test course. The corresponding tire pressures at the warning levels varied from 17.0 psi to 42.4 psi. The results are displayed by axle because some of the vehicles specified different air pressures front to rear. Also, the vehicle’s loading influenced the pressure loss threshold for these systems to sense underinflation. In all cases but one, more loading led to larger tire deflections that resulted in earlier warnings. On a winding road test course, it took between 36 and 625 seconds for the system to notify the driver that at least one tire was 50 percent underinflated.

Percentage Drop in Tire Pressure at TPMS Warning (Min. Pressure of 14 psi)

Load	Axle	System A	System B	System C	System D	Ave % drop
LLVW	Front	21 %	No Warning	40 %	28 % *	30 %
LLVW	Rear	16 %	No Warning	37 %	38 %	30 %
GVWR	Front	16 %	No Warning	18 %	31 % **	24 %
GVWR	Rear	9 %	No Warning	20 %	n/a	14 %

Note: Individual system percentages are the average of two trials, except where * indicates a single trial and ** indicates four trials.

For multiple WSB systems, after the system was reset the recalibration procedures did not work unless the vehicle was driven on a road with a large number of turns. None of the four systems evaluated indicated to the driver when the TPMS calibration was complete and the system was actively sensing tire pressure. The system that did not warn on the oval track did warn on a winding road course using the same reset and recalibration procedures prior to both tests. Therefore, it was concluded that a substantial portion of WSB systems require seeing rotational speed differences between the left and right wheels in turns to both calibrate the systems and sense tire underinflation.

To test the response of the WSB systems when the pressure rises above the activation level, 60 to 20 mph brake stops were performed with the tire at an initial pressure marginally below the experimentally determined activation pressure. None of the four systems' warnings extinguished due to the excessive tire heating (and rise in internal pressure). This was a good indication that the warnings will not flicker on and off once activated.

Two WSB TPMS equipped vehicles were tested to determine their activation pressure on a loose surface. The vehicles were tested on a 2.5 mile winding gravel road course at speeds ranging from 20 to 40 mph. A slow leak was initiated and vehicles were driven until TPMS warning activation or the tires had leaked down to a safety level of 14 psi. One system warned for one tire low at LLVW and at GVWR. It also warned for two diagonal tires low (RF/LR). The other system failed to warn for one tire low at both loading conditions. The system that did warn activated the warning much more quickly at LLVW than at GVWR. This was contrary to the findings on the paved surface for which increased loading generally helped the vehicle recognize underinflation.

The wheel-speed based systems must be reset if the inflation pressure in one or more tires is changed, if one or more tires is replaced or repaired, or if the tires are rotated. The reset procedure allows the WSB TPMS to "relearn" the rotational signature of each tire when it has changed due to one of the previously mentioned actions. If the systems are reset as recommended, the WSB TPMS may need to be reset up to 100 times during the life of a vehicle. Resetting the four WSB systems that were evaluated consisted of pushing a button on the dash or following a menu on a driver information console and then driving for a period of time to let the relearning (calibration) take place. Though none of the systems could be reset while the vehicle was in motion (to prevent defeating a warning), all four systems could be reset at rest without remedying the tire inflation problem. This would significantly impair or disable the ability of the system to provide an underinflation warning. Users should be cautioned to remedy the tire underinflation problem before resetting the system.

In general, the WSB systems have trouble detecting more than one tire low. Their underinflation warning threshold varies by axle and with load. Since changes in tire circumference with pressure are very slight in the 15 to 40 psi range, WSB systems generally require a 10 to 40 percent drop in pressure before they are able to detect underinflation. These warning thresholds cannot easily be changed by the manufacturer and are highly dependent on tire and loading factors. The time required to recognize a low tire pressure condition varied from one to ten minutes, depending on the system and the type of driving. The calibration procedures are prone to user error and the systems do not indicate when the system has calibrated and is functioning. From a longevity standpoint, these systems should last as long as the vehicle and are maintenance free. The ABS wheel speed sensors are well shielded and there exists little chance of damage from road hazards or tire changes.

Pressure-Sensor Based System Results

The following table presents the pressures at which the PSB systems' warnings were activated. The tires were filled cold to the placard pressure, the vehicle was placed on a lift (except for System E), and the air was let out in 2 psi increments until a warning occurred. The pressures were measured manually with a digital pressure gauge and averaged to produce the table entries.

Warning Activation Pressure Thresholds

System	E**	F	G	H	I	J
Placard Pressure:	**30 psi**	**30 psi**	**26 psi**	**30 psi**	**26 psi**	**30 psi**
Alarm:	**P / %ΔP**	**P / %ΔP**	**P / %ΔP**	**P / %ΔP**	**P / %ΔP**	**P / %ΔP**
Underinflation Advisory	n/a	17 psi / -42 %	n/a	24 psi / -20 %	n/a	24 psi / -19 %
Significant Underinflation	24 psi / -20 %	10 psi / -68 %	18 psi / -33 %	14 psi / -53 %	19 psi / -35 %	18 psi / -41 %

Each number is the average of two trials (right front and left rear tires)

* System I had an underinflation advisory, which was set at 25 psi. Because this level was only 1 psi below the placard pressure, false warnings were generated and this level could not be tested.

** System E could not be tested on a lift due to the test vehicles electronically controlled suspension. Thus, the results for System E are the average of eight outdoor trials.

As the table shows, for the systems that gave an underinflation advisory, this warning occurred between 17 and 24 psi (averaging 27 percent low). The significant underinflation warnings occurred between 10 and 24 psi (averaging 42 percent low). System F, still a prototype, had advisory and warning thresholds that were much lower than systems currently on the market. If System F's results are factored out, the advisory and warning thresholds for the PSB systems were 24 psi (20 percent low) and 18.6 (36 percent low) respectively. Two systems, both prototypes, had multiple occurrences of failing to warn during dynamic tests. The commercially available PSB systems always provided a warning.

The tests to explore temperature effects on PSB systems showed that systems that were not temperature compensated had less than a 1 psi change in their warning threshold levels for a 30 to 50°F change in ambient temperature. The one system tested that was temperature compensated shifted its underinflation advisory level down by 3.7 psi when going from 70 degrees F to 30 degrees F. It is thought that this feature is intended to help prevent nuisance warnings on days with large temperature fluctuations. The significant underinflation warning level for the systems tested was, by design, fixed and remained unaffected by the temperature changes.

The accuracy tests showed that those systems that displayed tire pressure readings were accurate to within 1 to 2 psi. System J also displayed a temperature compensated pressure intended to help the operator, especially when filling the tires, by calculating a cold tire pressure (as placard pressures are specified) from the current warm tire pressure. The deviation of the calculated cold pressure from placard (also displayed) would inform the consumer of how much air to add to the warm tires.

Some of the systems turned off their warnings after a series of brake stops or high-speed driving (used to heat the tires and raise the tire pressures). One system cleared its warning during the brake stop run and the high-speed run while another cleared its advisory only during the high-speed run. The system that had temperature compensation changed from a significant underinflation warning to an underinflation advisory. The remaining systems held their warnings despite rising internal tire temperature and pressure.

One of the static tests performed determined how quickly the systems would react to a sudden decrease in pressure. The test vehicle's rotating wheels were stopped (sensors active), the valves were opened, and the time to the first driver notification of underinflation, either an advisory or warning, was recorded. There was large variability in the time between a low-pressure event and the driver notification. The average response occurred in just over a minute. The fastest average response time for a system was 8 seconds while the longest response time for a significant underinflation warning was 136 seconds. These variations in response time reflect the differences in update times among systems. More specifically, some systems have the capability to sense an abrupt change in pressure and trigger a rapid transmission mode, alerting the driver more quickly.

To test the effects of a sensor failure, the left front sensor was removed for each of six PSB systems. The system was activated and the results recorded. Two systems warned of a sensor problem at startup. One system indicated zero pressure at startup but switched to a sensor error after fourteen minutes of driving. One system displayed a sensor failure warning message when the status button was pushed, but did not activate automatically. The remaining two systems warned of zero pressure but did not indicate that the problem was with the sensor.

The original equipment pressure-sensor based system had automatic sensor location recognition, a feature that eliminates retraining the receiver to new sensor locations after tire rotation. This system could be reset by pushing a button and then driving until the new locations were recognized. After tire rotation or replacement, one PSB system, whose sensor screwed on to the valve stems, needed to have the sensors screwed back on at the designated locations and the receiver reset. Another system required the new sensor locations to be retrained by a qualified technician. One system required manually retraining the sensor locations to the receiver by systematically lowering the tire pressure one tire at a time until the sensor activated. The final system evaluated had a "Tire Rotation Mode" that allowed the user to reassign sensors to tire locations on the receiver without activating a sensor by lowering tire pressure.

In general, the PSB systems were able to detect any combination of one or more underinflated tires. The warning thresholds were consistent from tire to tire and can be easily changed by the system manufacturer (or by the consumer on aftermarket systems). For systems that require the training of tire positions upon setup, the training process was tedious and difficult to accomplish. The results of the evaluation demonstrated that systems that automatically recognize the wheel locations of the sensors may be of benefit to consumers (though this feature usually requires the addition of antennas in each wheel well). Sensor batteries have a limited life span of five to ten years. The location of the tire sensors' metal valve stems or of the entire sensor (two of six) outside the tire makes them susceptible to road hazards, especially curb damage. As observed at the VRTC, PSB sensors can be damaged while mounting or un-mounting the tire to the rim. There is concern over emergency roadside tire inflation products (Fix-A-Flat®, etc.) possibly clogging up the in-tire sensors.

Human Factors Examination of Warning Displays

An examination of driver interfaces for existing TPMS showed significant variation in methods of visual warning presentation for both original equipment and aftermarket systems. Most of the visual displays were either difficult to see or hard to comprehend, or both. Auditory warnings were overall fairly similar amongst systems. The variation in visual warning presentation demonstrated the need for standardization of the visual warnings of tire underinflation to avoid driver confusion.

Low Tire Pressure Icon Comprehension Testing

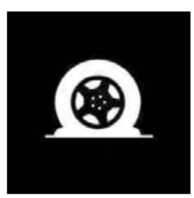
In response to negative comments regarding the recognizability of the ISO tire pressure icons and the lack of data regarding their ability to be comprehended by drivers (an investigation of the origin of the ISO tire pressure icons revealed they were not tested for comprehension prior to being added to ISO 2575), icon comprehension tests were conducted. The purpose of these tests was to assess the ability of two existing ISO icons and 13 alternative icons to alert drivers to the condition of low tire pressure. These 13 icons included 3 different wheel types (two 5 spoke wheels designs, one 7 spoke) applied to each of 4 icon versions (including whole wheel/tire profile, flat tire with an arrow pointing to it, and 2 different flat tire images). A total of 120 people were asked to look at a picture of one of the 15 icons and write a response to the question, "This image has just appeared on your vehicle's dashboard. It is a warning for ______________________________." The ISO engine icon was included on the sheet with each of the 15 icons to acquire data on its comprehension for use as a baseline. In all, 8 responses were received for each tire pressure icon and 120 responses for the engine icon.

Results of the initial comprehension test of the 16 icons showed that recognition percentages for the ISO tire pressure and tire failure icons were the lowest of the 16 icons tested, 38 percent and 25 percent, respectively. All of the 13 proposed alternative tire pressure icons had better comprehension percentages. Percent correct values observed for the alternative icons ranged from approximately 62 percent to 100 percent (6 of the 12 had 100 percent comprehension. Respondents showed near perfect (95 percent) comprehension results for the existing engine icon.

Selected Results from Icon Comprehension Test

Icon Version	N (out of 8)	% Correct
ISO Engine	114	95
ISO Tire Pressure (K.11)	3	38
ISO Tire Failure (K.10)	2	25
Wheel 2 - Flat 1	8	100
Vehicle (showed one tire highlighted to indicate low pressure in that tire)	6.5	81

Results of the comprehension tests showed that recognition was poor for the ISO tire pressure icons (K.10 and K.11). All of the icons proposed as alternatives to the ISO tire pressure icon were found to communicate at least some degree of tire inflation condition much better than the ISO icons. Based on these results, it is suggested that an alternative to the existing ISO icons be considered for use in warning drivers of low tire pressure. Considering the best recognized "wheel type" and best recognized "icon version", a single icon was identified as that which is most likely to be recognized by the general population. This icon is suggested for consideration as a visual indicator of significant tire underinflation and is pictured in the following figure.



Suggested icon for indication of significant tire underinflation.

Pictured in the following figure is a type of top-view vehicle display that could be implemented in vehicles for the presentation of low tire information. Use of this display would allow the presentation of tire specific information to the driver, i.e., tell which tire is underinflated. This type of display could be permitted as an alternative to, or in lieu of, a telltale. Of course a WSB system cannot detect which tire is low, only that one or more tires are low. Therefore, WSB systems would be limited to the use of a telltale.

Alternative vehicle-based display icon for presentation of tire underinflation warnings and information.

A full summary of findings from the examination of existing systems and icon development and comprehension testing follows in this report.

1.0 INTRODUCTION

Vehicles being operated with underinflated tires pose a significant safety problem. According to the Rubber Manufacturers Association, there were 647 fatalities in 1999 that involved "tire related factors" [1]. They further state that the "leading cause of tire failure is underinflation (which reduces tread life and generates excessive heat due to increased flexing)" [1]. According to Donald Shea, Rubber Manufacturers Association president and CEO, "The single most important factor in tire care is inflation pressure" [2]. Similarly, an article in ATZ Worldwide [3] estimates that 85 percent of tire failures are due to underinflation that results from gradual pressure loss.

A major contributing factor to this high rate of tire failures due to underinflation and gradual pressure loss is that many people do not know whether or not their vehicle's tires are properly inflated. As a result, many vehicles continue to be operated with underinflated tires. A recent survey conducted by Tire Business [4] of 766 vehicles found that:

> "...72.3 percent of vehicles were operating with at least one tire underinflated with an average underinflation of about 6 psi. 51.0 percent of the vehicles had at least one tire underinflated by 5 psi or more. 40.1 percent had all four tires low by an average of 7 psi….".

On November 1, 2000, the Transportation Recall, Enhancement, Accountability, and Documentation (TREAD) Act became law. One section of this Act deals with the above-mentioned problem through the following requirement:

> SEC. 13. Tire Pressure Warning: No later than one year after enactment the [National Highway Traffic Safety Administration] must complete a rulemaking to require a warning system in new motor vehicles to indicate to the operator when a tire is significantly underinflated. The rule must be effective within two years after completing the rulemaking.

This report documents research performed by the National Highway Traffic Safety Administration's (NHTSA) Vehicle Research and Test Center (VRTC) to assist in the above mandated rulemaking for light vehicles.

2.0 <u>OBJECTIVES</u>

The objective of this research was to assist the NHTSA with the TREAD mandated rulemaking by studying existing, light vehicle, Tire Pressure Monitoring Systems (TPMS). For as many models of TPMS as could be obtained, NHTSA's VRTC examined and tested each system to determine and document how it works, how accurate it is, when it warns of tire underinflation, and how it warns drivers of the condition of underinflation. It should be noted that though tire over-inflation leads to accelerated tire wear (in the center of the tread pattern), it is not known to be a significant safety issue.

The systems can be divided into two main categories, Wheel-Speed Based (WSB) and Pressure-Sensor Based (PSB) TPMS. WSB TPMS infer tire pressures by using the vehicle's ABS hardware, specifically the wheel speed sensors, to measure tire-to-tire differences in tire rotational velocities. PSB TPMS use pressure sensors mounted either in each tire or on each wheel to directly measure tire pressures.

Four vehicles equipped with Wheel-Speed Based TPMS were studied. For all of these vehicles, the vehicle manufacturer installed the WSB systems as original equipment. For each vehicle equipped with a WSB TPMS, the goals of the testing were to determine:

1. The accuracy of the TPMS.
2. The repeatability of the TPMS.
3. When the TPMS issues a warning to the driver.
4. How the TPMS issues a warning to the driver.
5. How to reset/train the TPMS when tires are replaced or rotated.

For vehicles with WSB TPMS, the TPMS cannot treat the tires independently. Therefore, for the appropriate tests, each vehicle was tested with multiple combinations of tires equally deflated. The combinations tested were:

1. Right front tire being deflated.
2. Left rear tire being deflated.
3. Right front plus left front tires being deflated (only two of the four vehicles).
4. Right front plus right rear tires being deflated.
5. Left front plus right rear tires being deflated.
6. Right front plus left rear tires being deflated.
7. Right front plus left front plus left rear tires being deflated.
8. All four tires being deflated.

Six Pressure-Sensor Based TPMS were studied. One of these PSB systems was original equipment on a vehicle, while the other five were installed on vehicles by VRTC. For each vehicle equipped with a PSB TPMS, the goals of the testing were to determine:

1. The accuracy of the TPMS.
2. The repeatability of the TPMS.
3. When the TPMS issues a warning to the driver.
4. How the TPMS issues a warning to the driver.
5. How to reset the TPMS when tires are replaced or rotated.
6. How the TPMS handles temperature effects.
7. What the TPMS does when the system fails.

For vehicles with PSB TPMS, the assumption was made that the TPMS for each tire functions independently. This was confirmed during pre-testing familiarization trials with various PSB systems. Therefore, for these tests, each vehicle/TPMS was tested twice dynamically, once with a front tire being deflated and once with a rear tire being deflated. Static tests on a vehicle lift or on jack stands were done indoors and outdoors to evaluate temperature effects on the PSB systems.

This study also examined the recognizability of underinflated tire warnings that were given to drivers, i.e., the human factors of the warnings. The visual and auditory displays used to present tire pressure warning information were examined. Comprehension Tests were conducted to determine the recognizability of two ISO tire pressure icons and 13 alternative tire pressure icons.

Methods used to reach these objectives are described in the following sections of this report.

3.0 SYSTEMS TESTED

Tire pressure monitoring technology is decades old. However, only recently has technology made these systems affordable and reliable for passenger vehicles. As a result, most of the systems available for evaluation were first generation systems or prototypes. NHTSA selected ten systems of varying configurations from manufacturers in Europe, Japan, and the USA.

As was mentioned in the preceding section, TPMS can be divided into two main categories, Wheel-Speed Based - WSB (Indirect) and Pressure-Sensor Based - PSB (Direct). WSB systems infer tire pressures by using the vehicle's ABS hardware, specifically the wheel speed sensors, to measure tire-to-tire differences in tire rotational velocities that indicate that a tire is at a different pressure from the others. PSB systems measure tire pressures directly with pressure sensors mounted either inside the tire or on the valve stem. The pressure reading is transmitted via radio signal to the control unit, which then indicates to the driver that the pressure is low.

3.1 Summary of TPMS/Vehicles Tested

The test systems and accompanying vehicles tested are listed in Table 3.1. A number of the systems tested were not yet on the market at the time this report was prepared or were still prototypes. Detailed descriptions of the driver interfaces are provided in Section 7.0, HUMAN FACTORS ASSESSMENT OF EXISTING TPMS DRIVER INTERFACES. The 10 systems tested are described in Table 3.1.

Table 3.1 – Tire Pressure Monitoring Systems and Vehicles Tested

System	Type	TPMS	Vehicle	Tires
A	WSB	Continental-Teves ABS with "Deflation Detection System" (DDS) BMW Motorsports "RDW System" (RDW: "Reifen Druck Warning" = "Tire Pressure Warning")	2001 BMW M3 Convertible*	Dunlop SP Sport 2000E 225/45 R17 91W
B	WSB	Delphi Delco 5.3 ABS with "Tire Inflation Monitoring" (TIM) Buick "Check Tire Pressure System"	2000 Buick LeSabre Custom*	General Ameri GS60 P215/70 R15 97S
C	WSB	Dunlop-Sumitomo ABS with "Warnair System" BMW AG "RPA System" (RPA: "Reifen Panne Anzeige" = "Tire Break-down Indication")	2001 BMW 750iL*	Michelin Pilot HX MXM4 ZP Zero Pressure (runflat) 235/55 R17 99H
D	WSB	Sumitomo ABS with "Warnair System" Toyota "Tire Pressure Warning System"	2000 Toyota Sienna CE*	Dunlop SP40 A/S P205/70 R15 95S
E	PSB	Beru AG "Tire Pressure Monitoring System" BMW AG "RDC System" (RDC: "Reifen Druck Control" = "Tire Pressure Control")	2001 BMW X5 European Spec*	Michelin MXV4 Pilot Radial XSE 255/55 R18 105H
F	PSB	Cycloid Co. "AutoPump" *Prototype*	1997 Ford Explorer XLT 4x4	Goodyear Wrangler RT/S P255/70 R16 109S
G	PSB	Fleet Specialties Co. "Tire Pressure Monitoring System" *Prototype*	2000 Honda CR-V SE	BF Goodrich Touring T/A SR4 205/70 R15 95S
H	PSB	Johnson Controls Inc. "Pressure Safety Information System" / Mirror Mounted Aftermarket Display	1997 Ford Explorer XLT 4x4	Goodyear Wrangler RT/S P235/75 R15 105S
I	PSB	Pacific Industries Co., LTD. "Pacific Tire Pressure Monitoring System"	2000 Honda CR-V SE	BF Goodrich Touring T/A SR4 205/70 R15 95 S M+S
J	PSB	SmarTire Inc. "Gen II SmarTire System" / with Full Function Display	1997 Ford Explorer XLT 4x4	BF Goodrich Touring T/A SR4 205/70 R15 95S

*TPMS was original equipment on that vehicle
WSB = Wheel Speed Based TPMS, PSB = Pressure-Sensor Based TPMS

3.1.1 Description of the Wheel-Speed Based TPMS Evaluated

Four WSB systems were tested as part of this research; all were fully integrated into the vehicle as original equipment on several makes of light vehicles. For each system, the following attributes are described:

- Method and conditions of warning presentation

- System Status Information
- Calibration

3.1.1.1 System A

Method and Conditions of Warning Presentation: System A had a single stage underinflation warning to inform the driver when the inflation pressure in one of the tires dropped significantly [5] (amount of pressure loss until activation was not given in owner's manual). This warning only occurred while the vehicle was being driven. The system warned the driver by illuminating the ISO K.11 icon on the instrument cluster (the right-most icon Figure 3.1) and sounding an auditory warning tone. The icon (the right-most icon in Figure 3.1) illuminated with the color red to show underinflation and the color yellow to show a system malfunction condition. System A allowed the driver to deactivate the system for driving with snow chains by pushing the system button on the dashboard, which then illuminated yellow.

The owner's manual warned:

- ***The (system) cannot alert you to severe and sudden tire damage caused by external factors***
- ***The (system) will not identify the natural, even loss of pressure in all four tires***
- ***Under certain circumstances, there may be false warnings or a delayed detection of losses in pressure when driving on snow-covered or slippery road surfaces***

A sporty driving style (slip at the wheels receiving the torque, high lateral acceleration) can lead to delayed (system) warnings [5]

Figure 3.1 – System A Test Vehicle / Significant Underinflation Warning Light (Rightmost)

System Status Information: System A indicated a system malfunction condition by illuminating the ISO tire failure icon (K.10) present within the instrument cluster with the color yellow.

Calibration: Calibration of the system was necessary after tire inflation pressure adjustment, tire rotation, or tire repair or replacement. To calibrate the system the driver had to turn the ignition to the accessory position (without starting the engine), and then depress the tire pressure warning system button until the indicator icon illuminated and then extinguished. System A's owner's manual stated that a few minutes of driving was sufficient for the current inflation pressure to be accepted as the reference value, and the system could then detect a flat tire. No notification was given to the driver that the initialization (calibration) process was complete. However, System A's manufacturer recommended the following procedure to NHTSA to achieve complete calibration:

> "Drive the vehicle for an hour in the speed range of 9 to 62 mph. Then, drive for 15 minutes each in the following speed ranges: 62 to 80 mph, 80 to 100 mph, 100 to 120 mph, and finally 120 to 155 mph. The system is then deemed fully ready to detect loss of tire pressure at any speed."

3.1.1.2 System B

Method and Conditions of Warning Presentation: System B had a one stage underinflation warning that was designed to alert the driver to a drop in pressure of at least 70 kPa (10 psi) in one of the tires [6] (activation pressure defined in owner's manual). This alert only occurred while the vehicle was being driven. If a low tire pressure was detected, the system activated an underinflation warning that consisted of the text message "CHECK TIRE PRESSURES" (Figure 3.2) accompanied by an auditory warning tone.

Figure 3.2 – System B Test Vehicle / TPMS Warning Message

The vehicle's owner's manual warned:

- ***Don't reset the (system) without first correcting the cause of the problem and checking and adjusting the pressure in all four tires. If you reset the system when the tire pressures are incorrect, the (system) will not work properly and may not alert you when a tire is low or high.***

The manual also warned that the system may give false warnings, delay warnings, or fail to warn under the following conditions:

- ***more than one tire is low***
- ***the vehicle is moving faster than 65 mph (105 km/h)***
- ***the system is not yet calibrated***
- ***the tire tread wear is uneven***
- ***the compact spare tire is installed***
- ***the tire chains are being used, or the vehicle is being driven on a rough or frozen road*** [6]

System Status Information: System B informed drivers that all tire pressures were satisfactory by providing the message, "TIRE PRESSURE NORMAL", in the driver information center. If System B detected a failure of a TPMS hardware component, the antilock brake system warning light would illuminate. However, the ABS warning light would not activate if the TPMS system failed to warn due to one of the eight causes listed in the owner's manual. These causes represent limitations in the sensing algorithm (software) that cannot be detected or accounted for.

Calibration: Calibration of the system was necessary after adjustment of the tire pressure, tire rotation, tire repair or replacement, and after the disconnection of the battery. System B's calibration was initiated by the driver resetting the system through a menu on the Driver Information Center. After the TPMS was reset, the car needed to be driven for 45 to 90 minutes. The system had two monitoring modes. The first was a partial monitoring mode with reduced sensing capabilities. Once full calibration was achieved, the system entered the second, "fully active" monitoring mode. To achieve full calibration, the vehicle had to be driven in three different speed ranges, 15 to 40 mph, 40 to 70 mph, and 70 to 90 mph. After completing this driving, the system was completely calibrated, according to the owner's manual, and ready to detect a loss of tire pressure. However, this system did not notify the driver when the state of full calibration had been achieved.

3.1.1.3 System C

Method and Conditions of Warning Presentation: System C had a one stage underinflation warning that alerted the driver of significant tire pressure loss by displaying the following message on the driver display: "TIRE DEFECT" (Figure 3.3) with an audible signal. The word "DEFECT" in the "TIRE DEFECT" message was a translation discrepancy that the vehicle manufacturer was reportedly addressing. The system could inform the driver of tire failure only while the vehicle was in motion.

Figure 3.3 – System C Test Vehicle / TPMS Warning Message

Figure 3.4 – System C Reset Button

The owner’s manual warned:

- ***the (system) cannot warn of sudden, severe tire damage caused by external effects***

The manual also warned that the system may give false warnings, delay warnings, or fail to warn under the following conditions:

- ***when the car is being driven with snow chains***
- ***when driving on snow-covered or slippery surfaces***
- ***if the car is driven in a very hard or enthusiastic manner (high lateral accelerations, wheel spin) [7]***

System C could be deactivated for use with snow chains. If a system malfunction was detected by the system, the information display would display “Tire Control Inactive”.

System Status Information: System C warned of a malfunction condition by either illuminating the ISO tire pressure icon (K.10), which was present within the instrument cluster, or by not illuminating the icon at all.

Calibration: Calibration of System C was required after tire pressure adjustments, tire rotation, or tire repair or replacement. System calibration was achieved by pressing and holding the reset switch found on the lower right instrument panel (Figure 3.4) and then driving the car for ten minutes. After this procedure was complete the system was stated to be ready to detect a significant loss of tire pressure.

3.1.1.4 System D

Method and Conditions of Warning Presentation: System D had a one stage underinflation warning that provided the driver with a warning when tire pressure in one of the tires was “critically reduced”. This alert only occurred while the vehicle was in motion. The system alerted the driver by illuminating the ISO icon K.11 on the instrument cluster (the middle icon in Figure 3.5).

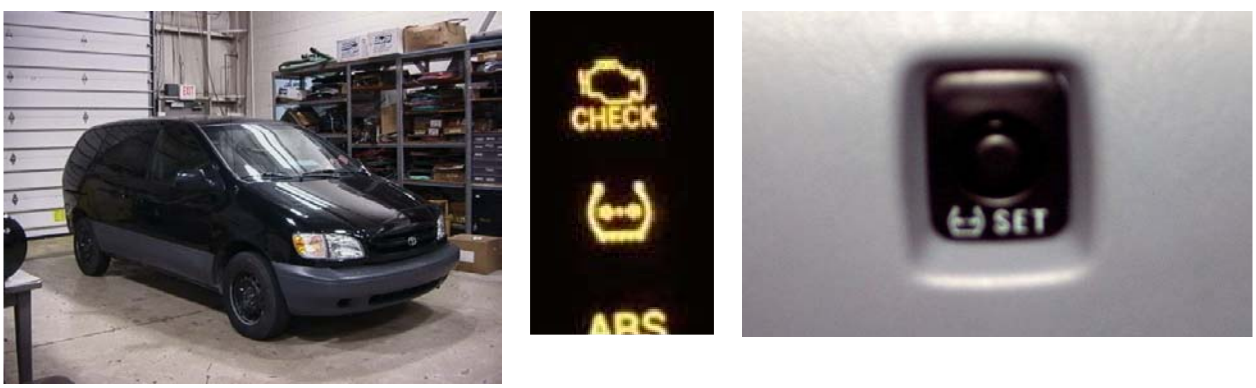


Figure 3.5 – System D Test Vehicle / Warning Light (Middle) / TPMS Reset Button

The manufacturer warned that the system may give false warnings, delay warnings, or fail to warn under the following conditions:

- ***if the tread wear is uneven among the installed tires***
- ***if a compact spare tire, snow tires, or tire chains are used***

- ***if the tire pressure is excessively higher than specified, or if the tire pressure is suddenly reduced due to bursts or other causes***
- ***if the vehicle is driven on a slippery road surface such as a rough road and frozen road***
- ***if the vehicle speed is less than 30 km/h (19 mph) or more than 100 km/h (62 mph), and if the driving duration is less than 5 minutes*** [8]

System Status Information: When the ignition was switched on, the TPMS light would illuminate for three seconds to indicate that the TPMS circuits were functioning. Since the operation of the TPMS was wheel speed information provided by the antilock brake system, a problem with the ABS hardware, more specifically the wheel speed sensors, would affect TPMS function. Thus, indication of ABS malfunction as indicated by illumination of the ABS warning light would also indicate a malfunction of the TPMS. There was no other indication of TPMS malfunction in addition to the illumination of the ABS warning light.

Calibration: Calibration of the system was required after tire rotation or tire replacement. This calibration was accomplished by pressing and holding the reset switch that was located on the lower left instrument panel (rightmost picture in Figure 3.5). Then, the car had to be driven at speeds above 19 mph for 8 hours before it was considered ready to detect loss of tire pressure. Though the 8hours of driving to calibrate the system was cumulative, allowing multiple driving sessions to achieve full calibration, no indication was given to the driver once the system was fully calibrated and in sensing mode.

3.1.2 Description of the Pressure-Sensor Based TPMS Evaluated

Six PSB systems were evaluated. One manufacturer installed a PSB TPMS on a vehicle as original equipment, while the other five systems were installed on test vehicles by VRTC. The PSB systems tested had a pressure sensor mounted either in each tire or on the valve stem or wheel. The sensors communicated with the receiver through radio waves. Each sensor had a unique digital identification code so that the particular tire with low pressure could be identified on the driver's display. The digital identification code also prevented signals from other vehicles' sensors from being analyzed by the TPMS. Most of these systems had an antenna built into the receiver; however, some had antennas mounted near the tires in the wheel wells. External antennas allowed automatic sensor location capabilities. Otherwise, the receivers had to be trained to the sensor locations. For each system, the following attributes are described:

- Sensor hardware
- Method and conditions of warning presentation
- System status information
- Calibration

3.1.2.1 System E

Sensor Hardware: System E was an original equipment pressure-sensor based TPMS. The sensor, which measured both tire pressure and air temperature, was inserted inside the wheel rim with a threaded aluminum valve stem replacing the original tire valve stem (Figure 3.6). Each sensor had its own identifying code. The vehicle manufacturer mounted antennas in each of the wheel well, which were then connected to the vehicle's ECU.

The stated accuracy of the system was ± 1 psi. Pressures are sampled by the system every 3 seconds but are transmitted every 54 seconds. In the case of a rapid loss of pressure, the system had the ability to cause the sensor to sample and transmit every 0.8 seconds. The temperature measurement was used to calculate the equivalent cold inflation pressure.

Method and Conditions of Warning Presentation: The driver interface for System E is shown in Figure 3.7. The system present on the European specification vehicle provided for testing had a single level of warning. This single warning level indicated the condition of significant tire underinflation and consisted of the text message "TYREPRESS" followed by either "FRONT" or REAR" and then "L." or "R." to indicate the specific tire that the warning referred to. The system used pre-stored values to evaluate tire pressure, but could also accept values supplied by the driver.

Figure 3.6 – System E Test Vehicle / Tire Sensor - Transmitter

Figure 3.7 – System E TPMS Warning Message With Wheel Location

System Status Information: No system status messages were observed during the testing of System E. However, according to the owner's manual, System E provided indication of system malfunction either by illuminating a yellow ISO K.11 icon on the dashboard or by displaying a text message stating "TYRECONTROL INACTIVE."

Calibration: Since System E had antennas installed in every wheel well, it could automatically recognize sensor locations from the relative signal strengths. Therefore, no additional location training was needed after installation or tire rotation. The system also monitored the inflation level of the spare tire. Warnings were displayed from a display located in the center of the instrument cluster (Figure 3.7).

3.1.2.2 System F

Sensor Hardware: System F was a prototype pressure-sensor based TPMS and tire inflation maintenance system. Tire pressures were sampled every 30 seconds and the status was transmitted every 10 minutes. The stated accuracy of the system was ± 1 psi. The pressure sensor, transmitter, and inertial driven pump are all contained in a sensor body that mounts to the center of the wheel (Figure 3.8). A special one-way pressure port was installed in a hole drilled through the wheel rim by the system manufacturer, necessitating specially modified rims to use this system. This port was then connected to the sensor/pump mechanism with a rubber hose. The hose allowed the hockey-puck sized sensor/pump unit to monitor current tire pressure and to pump additional air into the tires. An example of the inflation capabilities of this system can be seen in Appendix 2.

Method and Conditions of Warning Presentation: System F was designed to give two warning levels. The first was a "low pressure warning" designed to activate at 18 psi. The second was a "severe underinflation alert", which was designed to activate at 10 psi. However, since this version was a prototype of an original equipment system that was not commercially available, no driver interface was available for testing. Instead, a laptop computer was connected to the receiver to permit monitoring of the system.

Figure 3.8 – System F Test Vehicle / System F Wheel Sensor-Transmitter-Pump Unit

System Status Information: Due to the fact that this was a prototype system and a driver interface was not available for testing, the type of system status information that System F had the ability to present was not determinable.

Calibration: Since System F was a prototype, no standard calibration procedures were available at the time of testing. The system was calibrated by the manufacturer in preparation for the testing described in this report.

3.1.2.3 System G

Sensor Hardware: System G was also a prototype aftermarket pressure-sensor based TPMS. The sensor (Figure 3.9) replaced the cap on each valve stem. Each sensor had its own digital identification code. System G had the capability to receive signals from up to 22 tires simultaneously (it was adapted from a heavy truck application). The sensors' designated locations and cold inflation pressures were set at the factory. The sensors ordered for testing had a single warning threshold preset at 20 psi. This external mechanical-based sensor design did need to compensate its circuitry for temperature. The sensor and its battery could be installed and maintained without removing the tire. Sensor location identifiers could be updated to adjust the warning threshold if needed. The receiving unit contained the antenna and the driver interface. The stated accuracy of the system was ±1.0 psi.

Method and Conditions of Warning Presentation: The system was designed to give a single "low tire" warning. When tire underinflation was detected, the sensor would send a warning signal every 3.5 seconds until the pressure level was corrected. The warning signal consisted of a "LOW TIRE" text message as well as illumination of one of the four tires on the vehicle image display. There were no provisions to display tire pressure or temperature values. The driver interface for the system is shown in Figure 3.10.

System Status Information: System G provided only an indication that the battery was low. This indication was provided through the text "LOW BATT" which would appear in red in the center of the vehicle outline drawing present on the driver interface.

Figure 3.9 – System G Tire Sensor-Transmitter

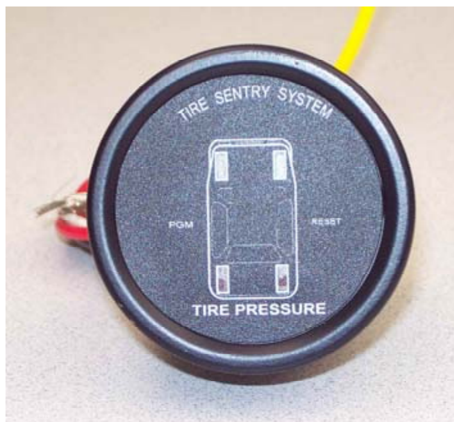


Figure 3.10 – System G Display

Calibration: System G's sensors screwed onto the valve stem and were labeled for each wheel position. Thus, the position of the sensors was intended to be fixed even in the event of tire rotation. Once the sensors are screwed back on or the inflation pressure problem is rectified (or low battery is rectified), A "RESET" button was present on the receiver and was used to clear any low battery (sensor) or underinflation warnings and to reset the system after removal of the sensors or adjustment of tire pressure.

3.1.2.4 System H

Sensor Hardware: System H was an aftermarket pressure-sensor based TPMS. The pressure sensor/transmitter is displayed in Figure 3.11. The sensor was inserted inside each wheel rim, with the aluminum valve stem replacing the tire valve stem. Each sensor had its own digital identification code. One antenna was contained in the receiving unit, which was mounted in a battery powered replacement rear-view mirror. Provisions to provide 12V power to the mirror are available. System H was the simplest aftermarket system to install and the least obtrusive since it did not require antennas or a 12V power cable to the cigarette lighter. The stated accuracy of the system was 2 to 5 percent, depending on the operating temperature.

Figure 3.11 – System H Sensor-Transmitter / Rearview Mirror Display

Method and Conditions of Warning Presentation: Tire pressure warning information was provided to drivers though a display that was integrated into the center rear-view mirror, as pictured in Figure 3.11. System H was designed to give two different levels of warning. The first was a "low pressure" warning, which occurred at 19.9 psi and consisted of a single auditory tone, or beep. The second was a "critically low pressure" warning, which occurred at 15.0 psi and consisted of a double beep. In both cases, the display alternated between the word "LO" and the measured pressure of the lowest tire. The tire indicator light for each low tire was also illuminated.

System Status Information: System H provided four different system status messages, each accompanied by a single beep. The first messages was the text "OK" which was presented at the first press of the toggle button or the first movement of the vehicle after the system had been awakened from "sleep mode". The system presented a "no pressure alarm" displayed as "nP" once batteries were replaced until new pressure data was received. A low receiver battery alarm was provided when the system was activated and the batteries in the receiver were low, displayed as "BAT LO". Lastly, the system presented a "transmitter failure alarm", displayed as "SF" along with the appropriate tire illuminated on the vehicle figure to indicate that no pressure information had been received from one or more sensors for more than 15 minutes.

Calibration: When first installed on a vehicle, the system had to be trained to recognize the identification code from each tire. This training was accomplished by first putting the display into the training mode. Then a magnet was held near the sensor on the left front wheel. The display would produce an auditory warning tone indicating that the wheel has been recognized and programmed into the system. The magnet was then moved to the right front, right rear, and left rear wheels, in that order. If the magnet training method failed, which could happen with large steel wheels, the sensors could be trained by a different method that involved deflating one tire at a time to train the receiver to sensor locations.

3.1.2.5 System I

Sensor Hardware: System I was an aftermarket pressure-sensor based TPMS. The sensor was inserted inside each wheel rim, with the aluminum valve stem replacing the original tire valve stem (Figure 3.12). Each sensor had its own digital identification code. One antenna was mounted in each wheel well, though one per axle may be sufficient depending on the size of the vehicle. The stated accuracy of the system was 1.8 psi.

Method and Conditions of Warning Presentation: The driver interface for System I is shown in Figure 3.13. System I monitored both pressure and temperature and could provide warnings for these conditions for each of the four tires individually. The system was designed to give four different levels of warnings. The first was a "below user target pressure" warning and auditory tone, which occurred when the pressure dropped below the level set by the user. The pressure was sampled every 15 seconds. Normally, data was transmitted every 10 minutes; but, in the case of a warning condition, it was transmitted every 15 seconds. The second warning was a "below warning pressure" alert and audible signal, which occurred at 20.3 psi. The third warning was a "decreasing tire pressure" warning that occurred when there was a loss of 2.9 psi in 15 seconds or a loss of 23.5 psi in 45 seconds. The fourth warning was the "temperature alarm" which activated when one of the tires' contained air reached 230 degrees F. The temperature or pressure could be checked at any time by the driver.

Figure 3.12 – System I Test Vehicle / System I Display and Tire Sensor-Transmitter

Figure 3.13 – System I TPMS Display

System Status Information: Upon vehicle ignition, System I would display tire pressure information. If tire pressures were in the normal range, pressure values are displayed for 10 seconds and then the visual display turns off. "System alarms" were provided to indicate data not received (no data received for at least one hour from a transmitter), alarm transmitter voltage drop, alarm transmitter status (four consecutive signals indicating alarm reception status were received), alarm data (four consecutive signals indicating out-of-range pressure, temperature, and voltage were received), receiver alarm (no data received for at least 20 minutes from all transmitters), and receiver voltage drop.

Calibration: When first installed on a vehicle, the wheels had to be registered for the system to recognize the identification code from each tire. This registration was accomplished by first putting the display into the registration mode. The position of the wheel was then entered (such as right front). Then air was let out of the right front wheel. The driver interface would emit an auditory warning tone indicating that the wheel has been recognized and programmed into the system. The display was then advanced and air was removed from the right rear, left rear, and left front wheels, in that order to complete the registration. Confirmation of registration was recommended and was accomplished by refilling all of the tires and then letting the air out of each tire one tire at a time while checking the display for the proper tire indication.

3.1.2.6 System J

Sensor Hardware: System J was an aftermarket pressure-sensor based TPMS. For testing purposes, this system was installed on the same vehicle used to test Systems F and H. In this evaluation the "Full Function Display" was tested since it had the capability of displaying current tire air pressure and temperature as well as temperature-compensated pressure levels and deviations from cold placard pressure. This information could be shown for each tire present on the vehicle individually. The sensor was fastened to the wheel with a metal band (Figure 3.14). Each sensor had its own digital identification code. The receiving unit contained the antenna and the display. The system monitored both pressure and temperature, which were sampled every 6 seconds. The internal tire air temperature was used to calculate the equivalent cold inflation pressure. The stated accuracy of the system was 1.5 psi for pressure and 5.4 degrees F for temperature. The system had the ability to monitor up to twenty tires.

Method and Conditions of Warning Presentation: The driver interface version tested in this program was the "Full Function Display", as shown in Figure 3.15. The system monitored each tire on the vehicle individually and was designed to give three different warnings. The first was a "pressure deviation alert" warning and tone, which occurred when the pressure dropped below the level set by the user. The second warning was a "low pressure warning" and a pulsed tone, which occurred at a level set by the operator. The third warning was the "high temperature alert" which activated when one of the tires reached a level set by the operator. The pressure deviation alert had optional temperature-compensated pressures, while the low pressure warning was fixed at a pressure level. The system allowed the driver to display the temperature, pressure, or deviation from placard of any tire by scrolling through the display. Separate displays for the vehicle and a trailer were available.

System Status Information: When power is applied to the receiver, all icons present on the multi-function display are momentarily turned on, the warning light blinks once, and a warning beep is sounded. The unit then goes blank. No data can be received until the vehicle is in motion. Once the vehicle is in motion, the system goes into stand-by mode (display shows vehicle outline and shaded rectangles representing tires from which signals have been received).

Calibration: When the system was first installed on a vehicle, the system had to be trained to the identification code from each wheel location. This learning sequence was accomplished by first putting the display into the learn mode. Air was let out of the first tire. The display would emit an auditory warning tone indicating that the wheel has been recognized and programmed into the system. A pause of a few minutes was required between wheels to allow time for the transmitter to stop transmitting. The display was advanced and air was removed from the next tire. This process was repeated until all the wheel codes have been learned. A separate mode allowed the user to reconfigure sensor locations after tire rotation.

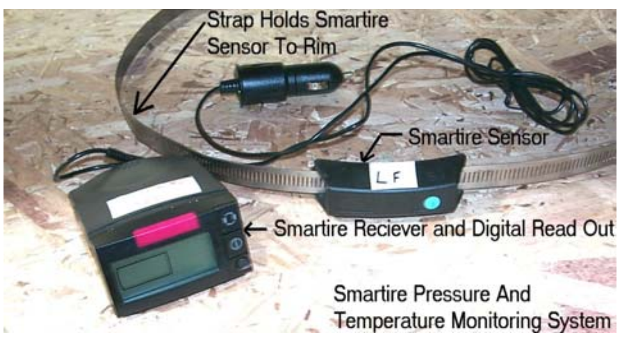


Figure 3.14 – System J / In-tire Sensor-Transmitter

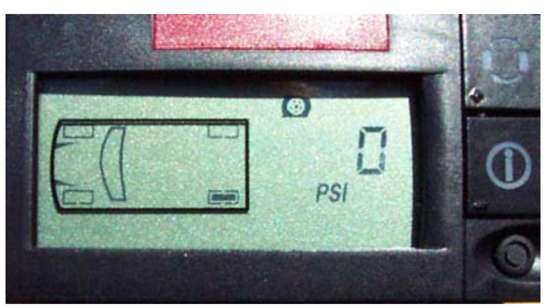


Figure 3.15 – System J "Full Function" Display

3.2 Wheel-Speed Based Tire Pressure Monitoring System Specifications

Wheel-speed based system specifications are limited since these systems consist of little more than an addition of software code to the ABS ECU and a warning light. As original equipment systems, their descriptions in the vehicle's owners and service manuals were user oriented and non-technical. Though the WSB systems use the ABS wheel-speed sensors to sense tire circumference, no specifications on ABS sensors' accuracies or update rates were available. Complicating this is the tendency of ABS manufacturers to closely guard the sensing algorithms of the ABS and the WSB TPMS. Though detailed information on activation threshold of the underinflation warning is not readily available, most systems claimed to warn when one tire dropped 20 to 30 percent below the other tires.

The vehicles' owner's manuals described how to operate the systems and warned of their limitations. For instance, all four owner's manuals cautioned that the WSB systems may give false warnings, delay warnings, or fail to warn under certain operating conditions or when used in conjunction with certain equipment such as tire chains or mini-spare tires. Owners were also cautioned against using tires not approved for their particular vehicle.

Currently, 1.6 million vehicles in the USA are equipped with wheel-speed based TPMS[1]. The cost of the WSB systems either to the manufacturer or the consumer was not available to VRTC at the time of this report. More than likely, the WSB systems were integrated to vehicles that were already equipped with ABS. Again, aside from research and development costs, the WSB TPMS costs consist mostly of adding software (and possibly minor electronics) to the ABS system and the addition of a warning light on the dash. Since the systems use the ABS wheel-speed sensors, which are simple and well protected, maintenance costs should be low.

3.3 Pressure-Sensor Based Tire Pressure Monitoring System Specifications

3.3.1 Cost

All six of the manufacturers of the PSB systems evaluated reported to have plans to produce their systems as original equipment on model year 2004 and later vehicles. Four of the six systems were

[1] Standard equipment on 11 GM models and an option on 1 Ford model

tested in aftermarket system configurations due to a lack of original equipment systems on the 2001 vehicles. Systems G, H, and I were intended as add-on displays until vehicle manufacturers adopt the tire monitoring systems as original equipment. System E is a good example of a pressure-sensor based system integrated into a vehicle as original equipment. This version was, however, the basic economy system and did not demonstrate the full functionality offered on other higher end models of this system. System F was a very early prototype and used a laptop computer to simulate the display. This system was primarily intended to be an integrated original equipment system.

Within the next few years, the PSB systems are expected to retain essentially the same tire pressure sensors but eliminate the add-on displays. The aftermarket receiver/display unit will be integrated into existing vehicle systems, lessening costs. The receiver portion of the display can be integrated into the vehicle's electronic control unit and perhaps interface though an existing key-less entry system. The display portion may be a simple telltale light on the instrument cluster or status messages on the driver information display.

Some manufacturers were able to estimate their original equipment cost per system (O.E. price) for large-scale production volumes. The aftermarket configurations have higher per unit costs due to the additional cost of an application specific receiver/display unit and the low production volumes.

Table 3.2 – Estimated Original Equipment and Aftermarket System Costs for PSB Systems

System:	**E**	**F**	**G**	**H**	**I**	**J**
O.E.M. Price per System:	\$50	No estimate	No estimate	\$50	No estimate	\$60
Aftermarket Price per System:	n/a	n/a	\$249	\$245 to 295	\$200	Basic \$150 Full \$250

Most manufacturers estimated the cost of integrated PSB TPMS to be under \$75 per vehicle for large supply volumes. The battery life of the current PSB sensors is about 7 to 10 years. Replacement costs for the tire sensors should be around \$10 to \$20.

3.3.2 Cold Inflation Pressure Ranges

The cold inflation pressure ranges of the six PSB TPMS will accommodate all light passenger vehicles. No light vehicle is known to operate at cold inflation pressures below 20 psi.

Table 3.3 – Cold Inflation Pressure Ranges for PSB Pressure Monitoring Systems

System:	**E**	**F**	**G**	**H**	**I**	**J**
Cold Inflation Pressure Range:	0 to 92 psi	0 to 55 psi	20 to 130 psi	20 to 62 psi	0 to 76 psi	10 to 75 psi

3.3.3 Mini-spare Tires

The upper cold inflation pressure thresholds of the PSB systems tested may need to be higher if high-pressure mini-spares are to be monitored. Though of benefit to consumers, monitoring spare tire pressures will complicate tire pressure monitoring. Monitoring of a mini-spare tire would require two pressure warning schemes, one for the four full-size tires and one for the mini-spare.

3.3.4 Warning Thresholds

The primary function of the TPMS is to warn of tire underinflation. Most pressure-sensor based systems have a two stage warning approach. The first driver notification of underinflation is an "underinflation advisory" meant to inform of low tire pressure that should be corrected at the next available opportunity. The second driver notification of underinflation is a "significant underinflated warning" meant to inform of a significantly, and dangerously low tire that must be immediately remedied. Table 3.4 summarizes the manufacturer's specified warning thresholds for the PSB systems.

Table 3.4 – Manufacturer Specified Warning Thresholds

System:	E	F	G	H	I	J
Type:	Original Equipment	Original Equipment	Aftermarket	Aftermarket	Aftermarket	Aftermarket
Underinflation Advisory Pressure Range:	Set by vehicle manufacturer	Set by vehicle manufacturer	n/a	15.1 to 19.9 psi Set by User	0 to 71psi Set by User	Off , 2.18 to 20.3 psi Set by User*
Underinflation Warning Pressure:	Set by vehicle manufacturer	Set by vehicle manufacturer	Preset for each vehicle	15 psi	20.3 psi	5.5 to 92.5 psi Set by User
High Pressure Warning:	None	None	None	None	None	None
High Temperature Warning:	None	None	None	None	≥ 248 °F	≥ 176 °F

*System J's underinflation advisory has a temperature compensated mode that can be toggled on and off. If the temperature compensation is active, the advisory pressure range may be affected.

PSB TPMS manufacturers chose varying approaches to setting warning limits. The aftermarket systems need the flexibility to accommodate any vehicle that the system may be installed in. For instance, aftermarket systems such as Systems H and I allowed the user to set the first warning threshold (underinflation advisory), but have a fixed lower warning threshold (significant underinflation warning). The basic version of System J, which had no user interface, would have the warning thresholds programmed by the TPMS dealer for a particular vehicle.

In this evaluation System J's optional Full Function Display was evaluated rather than the basic system. The Full Function Display allowed the user to set a desired tire pressure deviation from cold inflation pressure before the "Pressure Deviation Alert" (underinflation advisory), activates. This display also allowed the user to set the pressure level of the "Low Pressure Warning" (significant underinflation warning) for each axle. This was to accommodate vehicles that have different tire pressures for the front and rear axles.

It should be noted that none of the PSB TPMS warned for high tire pressure. Though tire over-inflation leads to accelerated tire wear (in the center of the tread pattern), it is not known to be a significant safety issue.

Systems I and J warned of high contained tire air temperatures. Tire manufacturers contend that high tire air temperatures are usually a result of operating with underinflated tires, and that warning for underinflation would eliminate the need for a high temperature warning. Significantly elevated tire air temperatures can damage the tires by evaporating the water content in the natural rubber that forms the tire carcass liner. Occasionally, high contained-air temperatures may occur when the tire is properly inflated but significantly overloaded or the vehicle has experienced prolonged braking. In this case, no TPMS warning would activate since the system perceives that the tire has sufficient pressure. Yet, the high temperatures may cause tire damage or failure if prolonged. The usefulness of high temperature warnings may warrant future research.

3.3.5 Temperature Ranges

Four of the six PSB TPMS have pressure / temperature sensors that mount inside the tire cavity. All semiconductor-based pressure sensors (five of the six PSB systems) must sense temperature to properly compensate their electronics for the drift induced by temperature changes. The compensation is limited to a normal temperature operating range. Within this temperature range a certain sensing accuracy is claimed. Also, most sensors have an environmental rating for peak temperature exposure without damage. Typically this is much higher than what will typically be experienced by the sensor. The normal operating range and peak environmental temperature ratings for each sensor are listed in Table 3.5.

Systems F and G have sensors that are installed outside the tire and therefore will see much lower operating and peak temperatures than the in-tire sensors.

Table 3.5 – Manufacturer Specified Temperature Ranges for PSB Pressure Monitoring Sensors

System:	**E**	**F**	**G**	**H**	**I**	**J**
Operating Temperature Range:	-40 to 248EF	-40 to 250EF	-4 to 149EF	-40 to185EF	-40 to 230EF	-40 to 185EF
Peak Temperature:	-40 to 338EF	-40 to 350EF	n/a	-40 to 248EF	-40 to 248EF	-40 to 257EF

3.3.6 Specified Pressure Accuracies

The accuracy of the sensing electronics varies with the operating temperature. Again Systems F and G were installed outside the tire and may have better accuracy due to a smaller temperature operating range for their electronics. The manufacturer's specified accuracies are listed in Table 3.6.

Table 3.6 – Manufacturer Specified Pressure Accuracies for PSB Pressure Monitoring Systems

System:	**E**	**F**	**G**	**H**	**I**	**J**
Accuracy:	±1.1psi: -4 to 158EF ±2.2psi: -40 to 212EF ±4.35psi: 212 to 248EF	±1psi	±1 % of F.S. (F.S. = 130 psi)	5 % F.S. -40 to 32EF 2 % F.S. 32 to 122EF 5 % F.S. 122 to 212EF (F.S. = 62 psi)	±1.8psi	±1.5psi

Overall, if normal operating conditions can be considered to be –20° to 120° F, then all systems claim an accuracy of ±2.2psi or better.

Test results of each system's warning accuracies are documented later in Section 6.0, RESULTS.

4.0 INSTRUMENTATION

Test sensors were attached to a PC-based in-vehicle data acquisition system (Figure 4.1) that recorded up to 10 channels at a rate of 20 Hz.

Figure 4.1 – Data Acquisition Computer

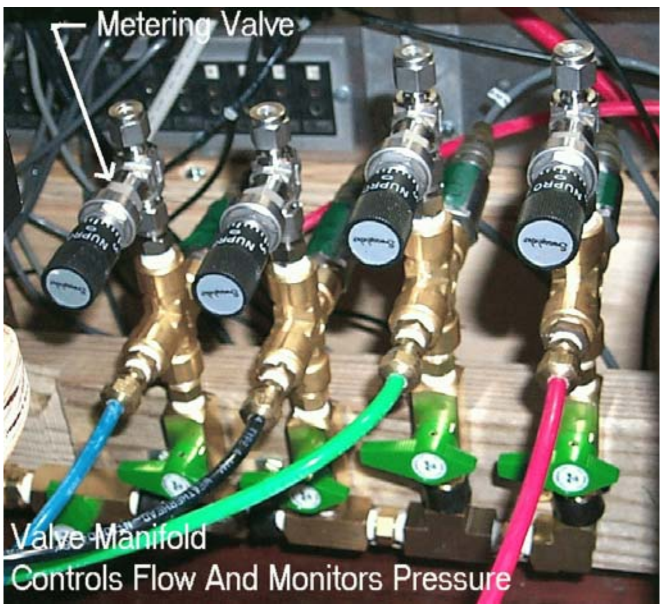
Table 4.1 provides a list of the measurement devices used to provide the data needed for this study.

Table 4.1 – Test Instrumentation

Description	Manufacturer	Application	Stated Accuracy (Range)	Location
Pressure Transducer	PSI-Tronix, PLC	Tire Pressure	±0.5 % of F. S. (up to 100 psig)	Vehicle Cabin
Temperature Sensor	Measurements Group, Inc.	Internal Tire Temperature	±0.1°F (-200° to 500°F)	Inside Tire Attached to the Rim
Warning Light Pickup	VRTC	Low Pressure Driver Warning	N/A	Instrument Panel/Dash
Driver Event	VRTC	Driver Input	N/A	Instrument Panel/Dash

The pressure metering valves and pressure transducers were installed on a manifold assembly that was located in the vehicle cabin (Figure 4.2). The manifold was connected to the tires via hoses and Deublin brand rotary air unions. An adapter plate, attached to each wheel with stainless steel standoffs, provided the connection between the stationary rotary union and the rotating wheel. A schematic of this plate is contained in Appendix 7.

Four Swagelok metering valves were used, one for each of the tires, to precisely leak tire pressure while the vehicle was in motion. The valves were given an initial setting and the orifice area was held constant throughout the test as the air pressure in the tires dropped. Keeping the valves set a constant orifice size meant that they simulated a hole in a tire of constant diameter. The implications of this are that pressure would leak out of the orifice more rapidly at higher pressures and decrease the leak rate as the tire pressure dropped.



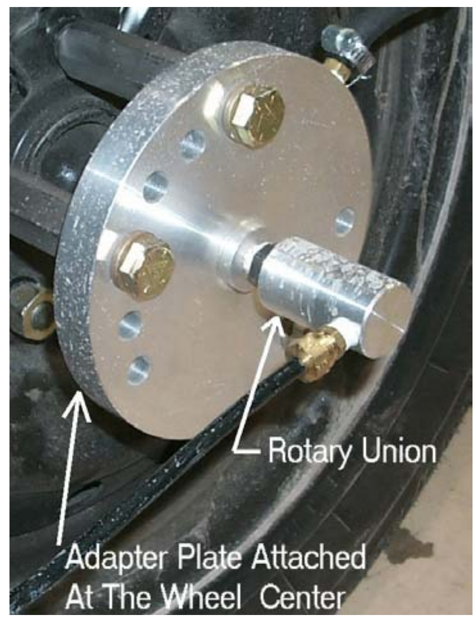


Figure 4.2 – Metering Valve and Control Manifold / Adapter Plate and Rotary Union

Four channels of data acquisition were dedicated to recording data from the four PSI-Tronix pressure transducers. Each transducer was attached to a cross fitting in the manifold assembly. The transducers measured the dynamic pressure at each of the four wheels during testing with an accuracy of ±0.5 percent of the 100 psi full-scale capacity (±0.5psi). All channels were filtered at 18 Hz to eliminate high frequency noise.

A telemetry based system for measuring internal tire temperatures consisted of four pairs of Measurement Group ETG-50B/W temperature sensors, Binsfeld BT 9000 Bridge Transmitters, and RD9000 Receivers. These sensors and transmitters were attached to each rim inside the tire cavity. The receivers, positioned in the vehicle cabin, received the temperature signals and transferred them as analog channels to the data acquisition unit. For certain test vehicles, the wheel/tire combination prohibited installation of the contained tire air temperature sensors. Therefore, internal tire temperatures are missing from the evaluations of the Systems A, C, and E.

A warning light detector (Figure 4.3) was designed and installed on the instrument panel near the steering wheel. The detector produced a voltage in response to activation of the low tire pressure warning light. The data acquisition computer recorded its voltage to determine the time of activation. Also on the dashboard was a switch the driver could use to indicate to the data collection system that a warning had activated.

Figure 4.3 – Warning Light Detector

For the static accuracy and temperature effects tests, a Radio Shack Sports Model stopwatch with split timing capability was used for time measurements. The watch had a stated accuracy of 1/100 of a second. The stopwatch was used to determine the reaction times to the first and second warnings issued by the various PSB TPMS. Video recordings of all tests were made using a Sony Digital MiniDV Handycam model DCR-TRV900 NTSC on Panasonic AY-DVM60EJ DV Cassettes.

Tire pressures were checked with an Intercomp Digital Tire Pressure gauge (Figure 4.4), accurate to "0.5 percent of applied pressure. The Intercomp gauge has a digital readout that displays pressures to the tenth of a psi. The accuracy of the Intercomp gauge was regularly calibrated with a Rochester Instrument Systems DPG-700-100 pressure gauge with a –10 to 100 psig range and ± 0.05 percent FS accuracy.

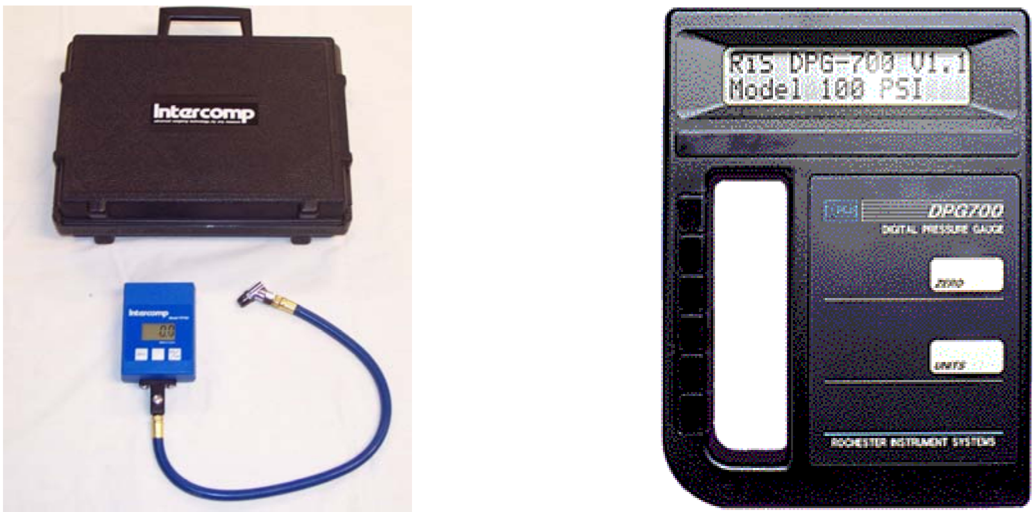


Figure 4.4 – Intercomp Digital Pressure Gauge / VRTC Calibration Standard Device

5.0 METHOD

Since the wheel-speed based and pressure-sensor based systems differed significantly in function, purpose, and capabilities, they required different types of evaluation procedures. The WSB systems use the antilock brake system's (ABS) wheel speed sensors to monitor individual wheel speeds while the vehicle is in motion. If the ABS ECU (Electronic Control Unit) detects a tire rotating faster relative to the other tires, that tire is thought to have a smaller rolling radius and therefore less inflation pressure. This means that the system relies on the calculated rolling radii (or circumference) of the tires to serve as a measure of inflation pressure. Evaluations of the WSB systems must therefore be performed with the tire rolling freely across a surface.

Another testing concern with WSB systems is that they may not function if the tires are rolling on loose, slippery, or uneven surfaces. Nor will they function properly if driven aggressively (inducing wheel slip). Therefore, the WSB systems were evaluated on smooth dry surfaces and driven at moderate speeds on the winding courses. (Limited WSB system testing was performed on loose, uneven, surfaces.) These concerns do not apply to PSB systems.

The PSB systems directly sense the tire air pressure and temperature at each tire. In theory, the PSB systems can function continuously, whether the vehicle is in motion or at rest. Though surface conditions do not impair sensing capabilities, the update rate of the PSB sensors is limited by FCC regulations and battery life concerns. Since the usual battery life conservation algorithms use wheel motion to activate and maintain sensors transmissions, evaluations of the PSB systems needed to take place with the tires in motion or being recently in motion. Therefore, the systems could be tested on a lift or jack stands as long as the tires were kept in motion (except for System E, which could not be tested off the ground due to activation of the electronic suspension's fault codes). For safety reasons, wheels speeds never exceeded 35 mph (56 km/h) when the wheels were off the ground.[2] As an additional safety precaution, any tire used in a low pressure TPMS test was rendered unusable when testing was completed.

The following test procedures were developed to verify the operation and accuracy of the available TPMS. These procedures were designed to determine at what point the systems alerted the driver to low pressure and if there were any conditions that prevented the systems from recognizing a low-pressure situation. These tests are not meant to represent a head-to-head comparison between different brands of the systems.

The following sections present a summary of the procedures used for both WSB and PSB TPMS. The detailed procedures can be found in Appendix 3.

5.1 Test Nomenclature

Table 5.1 shows the acronyms that are used in the following test matrices and in subsequent sections of this report. All driving courses used for testing were on the grounds of the Transportation Research Center (TRC) Inc. Appendix 5 contains maps of the High Speed Test Track and Winding Road Course.

Table 5.1 – Acronyms Used in Test Matrices and Subsequent Report Sections

Abbreviation	Explanation	Description
GAWR	Gross Axle Weight Rating	Door placard, GAWR
GVWR	Gross Vehicle Weight Rating	Door placard, GVWR
HSTT	High Speed Test Track	7.5 mile oval test track
LLVW	Lightly Loaded Vehicle Weight	Curb weight + 500lb
WGDC	Winding Gravel Durability Course	2.5 mile gravel road
WRC	Winding Road Course	1.5 miles of turns and straightaways

[2] This is based on a Dunlop Tire Safety Warning: The centrifugal forces generated by a free spinning tire/wheel assembly may cause sudden tire explosion resulting in vehicle damage and/or serious personal injury to you or a bystander. Never exceed 35 mph indicated on your speedometer. Never stand near or behind a tire spinning at high speed, as for example, while attempting to push a vehicle that is stuck or when an on-the-car spin balance machine is in use. Obtained from: http://www.dunloptire.com/tiretech/tirecare.html

5.2 Wheel-Speed Based TPMS

Since the WSB systems use wheel speeds to calculate the rolling radius of the tire, it was crucial that the tires had uniform tread wear, that the vehicle was properly loaded, and the tire pressures were set at the recommended placard cold inflation pressure while cold. Before testing, each WSB TPMS was reset and calibrated for each vehicle according to the manufacturer's recommended method (see the end of Appendix 4 – Calibration). The calibration procedure allowed the TPMS to learn the rotation properties of each tire and form a baseline expectation of the tires' rolling radii under different conditions. Since the dynamic rolling radius of a tire changes significantly with speed, the systems must be calibrated in multiple speed ranges. If a vehicle manufacturer recommends an increase in inflation pressure to accommodate a higher load, WSB systems require recalibration. For example, if a vehicle was to be tested at the gross vehicle weight rating at a specific tire pressure, it was also calibrated in that state.

System A, which was original equipment on a vehicle with an advanced variable differential, needed to be calibrated in multiple speed and engine torque ranges due to the differential's effect on driven wheel speeds. Therefore, multiple engine torque ranges were used during the hour of driving on the Winding Road Course.

5.2.1 WSB TPMS Calibration

During the calibration process, the WSB systems have little or no tire pressure sensing capabilities. To avoid extended periods without warnings when the TPMS is reset, the systems can be fully calibrated for discrete speed ranges. For example, the TPMS calibration of System B requires "about 10 minutes of straight line driving" in each of the following three speed ranges: 15 to 40 mph, 40 to 70 mph, and 70 to 90 mph [6]. Again, none of the four systems tested inform the driver of the status of the TPMS calibration. The driver is essentially unaware of the transition from a state without tire pressure monitoring during the calibration period to a partial or fully monitored state.

Since proper system calibration was so critical to the performance of each WSB system, the advised calibration times and speeds were met or exceeded for each of the test vehicles. A complete recalibration of the system was completed between test procedures that tested system accuracy or for tests at different vehicle loading.

Occasionally, instructions for the calibration of the TPMS in the owner's manuals were vague regarding the time necessary for calibration to be completed. For instance, the System D's owner's manual stated: "The initial adjustment (TPMS calibration) is completed after driving at the speeds of 30km/h (19mph) or over for about total 8 hours (sic), when the tire pressure warning system detects the normal tire pressures." [8]

An initial attempt to calibrate System D failed. In the first calibration attempt the vehicle was driven on the 7.5 mile High Speed Test Track (HSTT) for over 8 hours at three different speeds (30, 55, 75 mph equally). On the first day of testing, the system did not warn of the front right tire being severely underinflated (< 14 psi) and was deemed as not fully calibrated. Consultations with ABS and vehicle manufacturers led to the discovery that the two gradual right-hand turns on the high speed oval may not be sufficient to let the TPMS see differential wheel speeds when cornering. A new calibration course consisting of a winding course and high-speed figure eights was designed. When the new calibration course was run in multiple speed ranges, System D did achieve calibration. Details of the new calibration procedure can be seen in Appendix 1: Revised System D Calibration Procedures.

5.2.2 WSB TPMS Test Matrix

The following test matrix was used to evaluate the performance of the wheel-speed based systems.

Table 5.2 – Wheel-speed Based TPMS Test Matrix

Test	Criterion	Location
Sensing Capabilities Test	Ability to sense multiple tires low	WRC
First Accuracy Test – LLVW	Dynamic warning threshold	HSTT
Second Accuracy Test – LLVW	Repeat for accuracy	HSTT
First Accuracy Test – GVWR	Dynamic warning threshold	HSTT
Second Accuracy Test – GVWR	Repeat for accuracy	HSTT
Loose Surface Dynamic Test - LLVW	Loose surface warning threshold	WGDC
Loose Surface Dynamic Test - GVWR	Loose surface warning threshold	WGDC
Human Factors Evaluation	Functionality and user interfaces	Indoors & outdoors

5.2.3 WSB Test Procedures

All WSB systems were tested with the vehicle in motion. Initial tire pressure was set cold, and the vehicles were driven before each test to reach a "warmed-up" state. Up to eight different tests were run on each system (the Loose Surface Dynamic Test was only performed for two of the four systems). The first test was to determine if multiple low tires could be identified by the WSB systems. The second through fifth tests tested the systems' accuracy and response times at different loading conditions. The sixth and seventh tests were used to check if the systems could detect an underinflated tire on a loose road surface. Finally, the eighth test was used to evaluate the performance of the system from a human factors standpoint.

5.2.3.1 Sensing Capabilities Test

For the sensing capabilities test, it was necessary to test only whether the wheel-speed based system activated when multiple tires were low. WSB systems function better on roads with curves; hence, the Winding Road Course (WRC) was chosen. This test was intended to simulate a real-world scenario, with just the empty vehicle and driver for load. Each vehicle's TPMS was calibrated according to the exact procedures outlined by the manufacturer (Appendix 3). The tires started out being set at the recommended cold inflation pressure. There were seven combinations of low and normal inflation pressures tested, starting with one tire low and ending with all four tires low. Each tire designated to be low was set 50 percent below the current "warmed-up" pressure. The vehicle was driven more than 10 miles on the WRC to allow the system sufficient time to alert of the underinflated tire or tires. At the end of the test, each vehicle had different procedures to follow to reset the system after the tire was refilled to proper inflation pressure (Appendix 3).

5.2.3.2 First Accuracy Test – LLVW

The first accuracy test was used to determine at exactly what pressure the system activated (a good indicator of WSB system resolution). The vehicle was run in a lightly loaded condition (LLVW), which was vehicle curb weight plus up to five hundred pounds. While driving, air was slowly leaked out of the right front tire. The pressure at which the system warned of a low-pressure condition was noted. The tire was then refilled, the system reset, and the vehicle driven to determine when the system recognized that a normal condition had returned. After the tires were allowed to cool, the test was repeated using the left rear tire.

5.2.3.3 Second Accuracy Test – LLVW

The second accuracy test was a repeat of the first. The test was used to check the consistency of the threshold for the low tire pressure warning. A complete recalibration of the TPMS was done prior to conducting this test.

5.2.3.4 First and Second Accuracy Tests – GVWR

Additional accuracy tests were conducted using the same procedures described above, but with the vehicle loaded up to its gross vehicle weight rating (GVWR). Care was taken not to exceed the gross axle weight rating (GAWR) of either axle. A complete recalibration of the TPMS was done between the first and second tests.

5.2.3.5 Loose Surface Dynamic Test – LLVW

Wheel-speed based systems have trouble detecting low tire pressure on loose surfaces since they rely on wheel speed measurements. On loose surfaces, the wheels constantly change rotational speed due to varying levels of slip and non-uniform contact with the surface. To test the loose surface capabilities of the system, the vehicle was loaded to LLVW and the first and second accuracy tests were run on TRC's gravel road.

5.2.3.6 Loose Surface Dynamic Test – GVWR

As a continuation of the above test, the vehicle's load was changed from LLVW to GVWR and one accuracy test was performed on TRC's gravel road.

5.2.3.7 Human Factors Evaluation

A comprehensive human factors evaluation of each user interface was completed. The warning method was noted as an audible or visual signal, or both. For those systems that displayed a message, the context of the message was evaluated and message timing was noted. System failure messages were examined. The method of resetting the system was also assessed.

5.3 Pressure-Sensor Based TPMS

The PSB systems tested consisted of two original equipment (OE) and four aftermarket systems. The OE systems were configured at the factory and are fully functional upon delivery. These systems only require a change in settings if the tires, tire locations, or cold inflation pressures are changed. The aftermarket systems require about 1 to 3 hours of installation and configuration depending on the system. The installation of the aftermarket systems is generally straightforward. It consisted of installing a sensor in each rim, installing a receiver/display in the vehicle cabin, and if needed, installing antennas in the wheel well. The configuration consists of training the receiver to sensor locations and placard cold tire inflation pressures. Training the sensors to each tire location on the receiver was a critical part of the system setup, but as was discovered, very prone to user error.

5.3.1 PSB TPMS Sensor Training Methods

All of the aftermarket systems tested needed to have the specific tire sensor identification signal associated with a tire location at installation and after tire rotation. The OE systems that do not have antennas at each wheel well also need to be trained to the new location if the tires are rotated. To do this, the receiver is set to the learn mode and the sensor listed on the display is activated individually of the other sensors. Once a sensor location is learned, the person training the receiver moves on to do the other three sensor locations in an order dictated by the receiver display. This training process can be prone to user error, though the user will be alerted by the display that signals from a sensor(s) are not being received or if two are trained to the same location.

5.3.2 PSB Pressure TPMS Test Matrix

Table 5.3 contains the test matrix used to evaluate pressure-sensor based systems.

Table 5.3 – PSB Pressure TPMS Test Matrix

Test	Criterion	Location
First Warm Static Accuracy Test	Isothermal accuracy	Indoors on lift
Cold Static Accuracy Test	Temperature deviation effects	VRTC Parking Lot – Winter
Second Warm Static Accuracy Test	Repeat of isothermal accuracy	Indoors on lift
Dynamic Warning Thresholds Test - GVWR	Dynamic warning thresholds	HSTT
Loaded Dynamic High Speed Test - GVWR	High speed effects	HSTT
Human Factors Evaluation	Functionality and user interfaces	Indoors & outdoors
System Failure Effects Test	Sensor failure notification	HSTT

5.3.3 PSB Test Procedures

Each tire on a PSB pressure monitoring system has a pressure sensor located in it that is switched on by the rotational motion of that tire. Therefore, it is possible to test these systems as long as the wheels are in motion. Since multi-season testing was not possible, the PSB systems were tested in a heated laboratory, with the vehicle on a lift, and outside in winter weather, with the vehicle on jack stands. The systems' accuracy, temperature effects, and human factors tests were done with the vehicle elevated and the transmission in drive (except for System E). However, the dynamic warning thresholds were determined with the vehicles being driven on the test track (all systems). The effect of high-speed driving on the systems was also examined.

5.3.3.1 First Warm Static Accuracy Test

This procedure tested the accuracy and response time of the PSB pressure measurement system. The vehicle was tested indoors at 65 to 70°F. All the tires were filled cold to the placard pressure. The tires were spun at a speed equivalent to 20 mph for a minimum of 20 minutes to "wakeup" the sensors and give them two sensing cycles prior to the accuracy test. The wheels were then spun for 10 minutes at each pressure level to allow the system to update current tire status at least once. The right front tire pressure was reduced in steps of 2 psi until a warning was produced or the tire was flat. If the system has two levels of warning, the pressure continued to be decreased until the second warning was given (or the tire was flat). The right front tire was refilled and the procedure repeated for the left rear tire.

After completion of the above procedures, a rapid tire deflation test was performed. This test measured the response time of the first and second warnings to a tire puncture. This test was first performed on the left front tire and then repeated using the right rear.

5.3.3.2 Cold Static Accuracy Test

This test evaluated the effects of temperature changes on PSB system performance. It simulated the changes in temperature as the seasons of the year change. A main concern was the influence of temperature compensation on warning thresholds levels.

Tire pressures were set according to the placard inside the laboratory (around 72°F). Then the vehicle was moved outside in the cold for overnight storage. The next day, the tire pressures were recorded, but not adjusted. The tests described in the First Static Accuracy Test Section were then performed.

5.3.3.3 Second Warm Static Accuracy Test

This test was a repeat of the first static test and was used to evaluate the repeatability of the warning thresholds. This test was performed indoors, with the vehicle on a lift and the tires rotating.

5.3.3.4 Dynamic Warning Thresholds Test – GVWR

Dynamic Warning Thresholds tests evaluated the on-road response of the PSB systems to a slow leak and also a medium-sized tire puncture. The vehicle was initially loaded to its GVWR, being careful not to exceed the GAWR of either axle. The vehicle was driven at 60 mph and air was slowly released from the right front tire. The release of air stopped when the TPMS warning activated (first warning level) or the tire pressure reached 14 psi. The right front and left rear tires were tested at both leak rates.

In addition, while tire was at the warning threshold pressure, brake snubs were completed to heat the tires and raised pressure back above the threshold. If the warning shut off at a tire pressure marginally above the threshold, it was an indication that warnings would flicker on and off.

5.3.3.5 Loaded Dynamic High Speed Test – GVWR

Loaded dynamic high-speed tests were conducted at gross vehicle weight ratings to explore the effects of high vehicle speeds on the TPMS threshold. High speed heats the tires, raises the pressure inside, and may extinguish the low tire pressure warning. This test was similar to the previous test except that high speed was substituted for the brake snubs to heat the tires.

The loading condition was maintained from the previous test. The left rear tire was deflated to a pressure 2 psi below the average pressure that caused a warning in the indoor static tests. The vehicle was driven at 20 mph until the system detected low tire pressure. If low tire pressure was not detected, the pressure was lowered by 2 psi until a warning was given or the pressure reached 14 psi. The vehicle was then driven at 75 mph for 22.5 miles (3 laps) and the state of the warning system was noted.

5.3.3.6 Human Factors Evaluation

A comprehensive human factors evaluation of each user interface was completed. The warning method was noted as an audible or visual signal, or both. For those systems that displayed a message, the context of the message was evaluated and the message timing was noted. System failure messages were also examined.

5.3.3.7 System Failure Effects Test

Since consumers may tend to rely on this monitoring system as a warning system, the driver must be alerted to a system failure. Of particular importance for PSB systems is a warning of individual tire sensor failure(s). Therefore, one sensor was either disabled or removed and the vehicle was driven until a system failure warning was detected or 30 minutes had elapsed. The response of the system was recorded.

6.0 RESULTS

6.1 Wheel-Speed Based TPMS

Four wheel-speed based tire pressure monitoring systems were evaluated. The tests performed focused on sensing capabilities, warning thresholds, accuracy, and driver interfaces. The results from the evaluation should be considered on a per vehicle basis rather than for a specific ABS/TPMS manufacturer. This is due to the fact that the vehicle manufacturer will often co-develop the TPMS sensing algorithms with the ABS manufacturer and has control over the final installation of the system. A TPMS from a given ABS manufacturer may be integrated quite differently from vehicle to vehicle.

6.1.1 WSB Sensing Capabilities Test

The purpose of this test was to determine if the systems could sense multiple low tires simultaneously. Attempts were made to test the WSB systems under real world conditions. The vehicles were tested lightly loaded, simulating the normal operating mode of most light vehicles. Test tires were deflated by 50 percent to significantly exceed the approximate 30 percent low warning threshold of WSB systems. Testing was conducted in dry conditions on the Winding Road Course (Appendix 5) so that the WSB systems could see differential side-to-side wheel speeds. This course selection was motivated by earlier testing where it was discovered that vehicles with WSB systems may not warn during straight-line driving (but will on roads with turns).

Tires were deflated to 50 percent below the warmed-up placard tire pressure in combinations ranging from one to all four tires simultaneously low. The warmed-up placard tire pressure is defined as follows: Test vehicles were moved outside and allowed to sit for a minimum of one hour prior to testing. Before driving a test vehicle, each tire was set outdoors to cold placard inflation pressure. The vehicle was then driven out to the Winding Road Course and driven for two laps to warm up the tires. The inflation pressure obtained in this manner is defined as the warmed-up placard tire pressure. The respective test tires were then deflated to 50 percent below the warmed-up placard tire pressure. With the tire(s) low, the vehicles were driven for more than 10 miles at approximately 30 mph to allow the WSB systems a reasonable amount of time to sense and warn of the significantly underinflated tires. Table 6.1 documents the distance traveled and approximate time required for the WSB systems to give a warning for each combination of low tires.

Table 6.1 – Results of Sensing Capabilities Test for WSB TPMS on the Winding Road Course

TIRE(S) 50 % LOW	SYSTEM A		SYSTEM B		SYSTEM C		SYSTEM D	
	Miles	minutes	miles	minutes	Miles	minutes	miles	minutes
One Tire, RF	1.6	2.1	2.9	4.8	1.1	1.7	1.5	2.5
One Tire, LR	1.5	2.0	5.2	8.7	2.5	3.8	0.5	0.8
Two Tires, Right Side	No Warning	>14	No Warning	>18	No Warning	>16	No Warning	>18
Two Tires, Front Axle	*	*	No Warning	>18	*	*	No Warning	>18
Two Tires, Diagonal - RF/LR	No Warning	>14	4.4	7.3	0.8	1.2	0.8	1.3
Two Tires, Diagonal - LF/RR	No Warning	>14	1.7	2.8	1.3	2.0	0.3	0.5
Three Tires	3.1	4.1	1.0	1.7	1.6	2.4	0.8	1.3
Four Tires	No Warning	>14	No Warning	>18	No Warning	>16	No Warning	>18

*Test not performed

>minutes: reflect systems that did not warn in the time required to travel 10.5 miles (7 laps) around the Winding Road Course

6.1.1.1 One Tire Significantly Underinflated

All four systems warned of one front or rear tire that was 50 percent underinflated. The distance each vehicle required to sense the low tire pressure and activate the TPMS warning ranged from 0.5 to 5.2 miles. Activation times ranged from 0.8 to 8.7 minutes for one tire low.

6.1.1.2 Two Tires on the Same Side of the Vehicle Significantly Underinflated

All four systems failed to warn of two tires on the same side of the vehicle 50 percent underinflated. After 7 laps (10.5+ miles) on the WRC, the tests were terminated. Total elapsed time for each test ranged from 14 to 18 minutes, during which no warning was observed.

6.1.1.3 <u>Two Tires on the Same Axle Significantly Underinflated</u>

Due time and weather constraints, only two of the four WSB systems were tested for two tires on the front axle underinflated. After more than 18 minutes of driving, both systems had failed to warn of 50 percent underinflation in two tires on the same axle (front).

6.1.1.4 <u>Two Tires at Diagonal Positions Significantly Underinflated</u>

Three of the four WSB systems warned of underinflation at both diagonals (RF/LR and LF/RR). The distance to warning ranged from 0.3 to 4.4 miles. The time to warning ranged from 0.5 to 7.3 minutes. The one vehicle that did not warn had an advanced drive train may have hampered TPMS sensing at diagonal locations. This will be discussed in greater detail in the discussion in Section 9.1, WSB Systems.

6.1.1.5 <u>Three Tires Significantly Underinflated</u>

All four systems warned of three tires low. The distance to warning ranged from 0.8 to 3.1 miles. The time to warning ranged from 1.3 to 4.1 minutes. Sensing three tires low is essentially the same as sensing a single tire that is overinflated or underinflated.

6.1.1.6 <u>Four Tires Significantly Underinflated</u>

All four systems failed to warn of four tires equally underinflated by 50 percent. The seven test laps on the WRC lasted 14 to 18 minutes, during which no warning was observed.

An explanation for the failure of the WSB systems to warn in three scenarios of the Sensing Capabilities Test is contained in the discussion in Section 9.1**,** WSB Systems.

6.1.2 <u>WSB Dynamic Warning Threshold & Accuracy Tests</u>

The vehicles equipped with WSB systems were instrumented to record both tire air pressure and contained air temperature, in real time. A series of slow leak-down tests at lightly laden and fully laden vehicle weights were performed on the High Speed Test Track (Appendix 5) to determine TPMS activation levels. Since the initial tire temperature and pressure were critical for the WSB systems, tires were allowed to cool outside for an hour between each test run. This was not done for the PSB systems since initial tire conditions were not as critical.

The dynamic warning thresholds of the WSB systems were determined by monitoring the tire pressure and TPMS system while the tire pressure was slowly leaked down at a rate of 1 to 2 psi per minute. Note that since this is dynamic testing, with the vehicle being driven, the tire pressure being monitored is the **warm** inflation pressure. The air pressure-venting device was a 0.25 inch needle valve opened two turns (of 9.5 total turns) to create a uniform flow rate, vehicle to vehicle. Tire size, relative placard pressure, and observed vent flow rate information (based on the measured, warm, inflation pressure) observed during testing is summarized in Table 6.2. These flow variations indicate that the same size hole in different tires will leak down at slightly different rates, but that a very low pressure condition would result from all of them in 15 to 30 minutes.

Table 6.2 – Observed Vent Flow Rates for WSB TPMS-Equipped Vehicles

Test Vehicle	Relative Tire Size	Placard Pressures	Approximate Leak Rate
System A	Small (low profile)	33/38 psi; 36/46 psi	2.0 psi/min
System B	Large	33 psi	1.0 psi/min
System C	Large, run-flat	29/32 psi; 35/39 psi	1.1 psi/min
System D	Medium	35 psi	1.2 psi/min

Note: Placard pressures are front/rear @ LLVW; front /rear @ GVWR for

The complete set of warning threshold measurements for WSB systems can be found in Table 6.3. If we assume that the time required for WSB systems to activate after the tire inflation pressure has fallen below the level required to trigger a warning does not change from a sudden to a more gradual air loss, then the data in Table 6.1 can be combined with the data contained in Table 6.3 to calculated the warm tire inflation pressure required to trigger a warning. The results of this calculation are shown in Table 6.4.

A summary of the activation levels, in terms of percentage drop in tire pressure from cold inflation pressure, are listed in Table 6.5. Percentages are used since the vehicles' placard pressures often differ from front to rear axles and between loading conditions. The values listed in Table 6.5 are the average of two trials for the same axle and same test conditions. It should be noted that tire heating, caused by the 60 mph test speed, resulted in the initial warm inflation pressures being a few psi higher than the original cold placard pressure level.

Table 6.3 – Complete WSB System Test Results

Tire	System	Placard Pressure (psi)	Loading	Deflation Rate (psi/min)	Warm Pressure when Underinflation Warning Occurred (psi)	Percent Loss of Placard Pressure	Time Until Warning (min)	Ambient Air Temp. (°F)
RF	A	36	GVWR	2.0	27.1	25 %	4.5	34
LR	A	46	GVWR	2.1	37.6	18 %	4.0	40
RF	A	36	GVWR	1.8	25.9	28 %	5.6	24
LR	A	46	GVWR	2.2	38.0	17 %	3.6	25
RF	A	33	LLVW	1.6	23.3	29 %	6.1	24
LR	A	38	LLVW	1.7	28.2	26 %	5.8	22
RF	A	33	LLVW	1.6	22.0	33 %	6.9	30
LR	A	38	LLVW	1.7	29.0	24 %	5.3	33
RF	B	33	GVWR	1.0	none @ 14.0	n/a	n/a	52
RF	B	33	GVWR	1.0	none @ 13.7	n/a	n/a	44
LR	B	33	GVWR	1.0	none @ 13.9	n/a	n/a	54
RF	B	33	LLVW	1.0	none @ 13.5	n/a	n/a	38
LR	B	33	LLVW	1.0	none @ 13.9	n/a	n/a	47
RF	C	32	GVWR	1.1	24.6	23 %	6.7	38
LR	C	39	GVWR	1.3	24.1	38 %	11.5	47
RF	C	32	GVWR	1.1	24.5	23 %	6.8	37
LR	C	39	GVWR	1.2	29.1	25 %	8.3	41
RF	C	29	LLVW	1.0	15.3	47 %	13.7	41
LR	C	35	LLVW	1.1	17.6	50 %	15.8	42
RF	C	29	LLVW	1.1	16.0	45 %	11.8	41
LR	C	35	LLVW	1.2	18.2	48 %	14.0	41
RF	D	35	GVWR	1.4	19.6	44 %	11.0	26
RF	D	35	GVWR	1.4	22.5	36 %	8.9	42
RF	D	35	GVWR	1.4	18.4	47 %	11.9	34
RF	D	35	GVWR	1.3	23.0	34 %	9.2	33
RF	D	35	LLVW	1.3	21.8	38 %	10.2	33
LR	D	35	LLVW	1.2	18.1	48 %	14.1	34
LR	D	35	LLVW	1.2	23.7	32 %	9.4	33

Table 6.4 – Calculated Pressures to Trigger WSB Warnings

Tire	System	Placard Pressure (psi)	Loading	Deflation Rate (psi/min)	Warm Pressure when Underinflation Warning Occurred (psi)	Time to Trigger Warning (from Table 6.1) (min)	Calculated Pressure to Trigger Warning (psi)	Percent Loss of Placard Pressure to Trigger Warning
RF	A	36	GVWR	2.0	27.1	2.1	31.3	13 %
LR	A	46	GVWR	2.1	37.6	2.0	41.8	9 %
RF	A	36	GVWR	1.8	25.9	2.1	29.7	18 %
LR	A	46	GVWR	2.2	38.0	2.0	42.4	8 %
RF	A	33	LLVW	1.6	23.3	2.1	26.7	19 %
LR	A	38	LLVW	1.7	28.2	2.0	31.6	17 %
RF	A	33	LLVW	1.6	22.0	2.1	25.4	23 %
LR	A	38	LLVW	1.7	29.0	2.0	32.4	15 %
RF	B	33	GVWR	1.0	None @ 14.0	n/a	n/a	n/a
RF	B	33	GVWR	1.0	None @ 13.7	n/a	n/a	n/a
LR	B	33	GVWR	1.0	None @ 13.9	n/a	n/a	n/a
RF	B	33	LLVW	1.0	None @ 13.5	n/a	n/a	n/a
LR	B	33	LLVW	1.0	None @ 13.9	n/a	n/a	n/a
RF	C	32	GVWR	1.1	24.6	1.7	26.5	17 %
LR	C	39	GVWR	1.3	24.1	3.8	29.0	26 %
RF	C	32	GVWR	1.1	24.5	1.7	26.4	18 %
LR	C	39	GVWR	1.2	29.1	3.8	33.7	14 %
RF	C	29	LLVW	1.0	15.3	1.7	17.0	41 %
LR	C	35	LLVW	1.1	17.6	3.8	21.8	38 %
RF	C	29	LLVW	1.1	16.0	1.7	17.9	38 %
LR	C	35	LLVW	1.2	18.2	3.8	22.8	35 %
RF	D	35	GVWR	1.4	19.6	2.5	23.1	34 %
RF	D	35	GVWR	1.4	22.5	2.5	26.0	26 %
RF	D	35	GVWR	1.4	18.4	2.5	21.9	37 %
RF	D	35	GVWR	1.3	23.0	2.5	26.3	25 %
RF	D	35	LLVW	1.3	21.8	2.5	25.1	28 %
LR	D	35	LLVW	1.2	18.1	0.8	19.1	46 %
LR	D	35	LLVW	1.2	23.7	0.8	24.7	30 %

Table 6.5 – Percentage Drop in Pressure to Trigger WSB

Leak Rate (psi/min)	Load	Axle	System A (% drop)	System B (% drop)	System C (% drop)	System D (% drop)	Average (% drop)
1 to 2	LLVW	Front	21 %	No Warning	40 %	28 % *	30 %
1 to 2	LLVW	Rear	16 %	No Warning	37 %	38 %	30 %
1 to 2	GVWR	Front	16 %	No Warning	18 %	31 % **	24 %
1 to 2	GVWR	Rear	9 %	No Warning	20 %	n/a	14 %

Note: Individual system percentages are the average of two trials, except where * indicates a single trial and ** indicates four trials.

The highest warning threshold was observed from tests of System A with the rear axle tires at GVWR. The warning activation was seen at an average value of 9 percent below the placard pressure. In pressure terms this corresponds to an average warning threshold of 42.1 psi for the 46 psi placard pressure. The lowest average warning threshold, 40 percent low, was observed for tests of System C with the rear axle tires at LLVW. This corresponds to an average warning threshold of 17.5 psi for the 29 psi placard pressure. It should be noted that System C's test vehicle, unlike the other vehicles, had extremely stiff Michelin Zero Pressure (run-flat) tires that may have limited its sensing capabilities in the lightly loaded condition. However, the ultra low profile, high performance tires on System A's test vehicle had very stiff sidewalls, yet had the highest warning threshold.

While there was little difference in the results from axle to axle, the results in Table 6.5 demonstrate that the TPMS activation level was definitely influenced by the amount of tire loading. On average, the WSB systems were more sensitive at GVWR, than at LLVW, activating less pressure loss at GVWR. The range actual pressure warning levels for each system are listed in Table 6.6 below.

Table 6.6 – Range of Tire WSB Systems' Pressure Warning Levels

TPMS System	Highest Warning Pressure (Cold Inflation Pressure)	Lowest Warning Pressure (Cold Inflation Pressure)
System A	41.8 psi (46 cold)	25.4 psi (33 cold)
System B	No warning down to 14.0 psi (33 cold)	No warning down to 14.0 psi (33 cold)
System C	33.7 psi (39 cold)	17.0 psi (29 cold)
System D	26.3 psi (35 cold)	19.1 psi (35 cold)

Note: The inflation pressures listed were the maximum and minimum pressures observed for either loading condition.

As Table 6.6demonstrates, the warning activation pressures for the four WSB systems ranged from 17.0 to 41.8.0 psi (starting at 29 and 46 psi cold respectively). Therefore, the pressure level at which the WSB Systems can sense tire underinflation differs significantly from vehicle to vehicle and is highly dependent on the amount of vehicle loading, the type of tires, and the initial placard pressure.

The accuracies of the four WSB systems are listed in Table 6.7 below.

Table 6.7 – Range of Warning Thresholds and Repeatability of the Warning Level

TPMS System	Axle	Range of Warnings (Percent Below Placard)		Average Warning Level (Percent Below Placard)		Standard Deviation of Warning (Percent of Placard)	
		LLVW	GVWR	LLVW	GVWR	LLVW	GVWR
A	Front	19 to 23 %	13 to 18 %	21 %	16 %	3 %	3 %
A	Rear	15 to 17 %	8 to 9 %	16 %	9 %	1 %	1 %
B*	Front	-	-	-	-	-	-
B*	Rear	-	-	-	-	-	-
C	Front	38 to 41 %	17 to 18 %	40 %	18 %	2 %	0 %
C	Rear	35 to 38 %	14 to 26 %	37 %	20 %	2 %	8 %
D	Front	28 %**	25 to 37 %**	28 %	31 %**	n/a	6 %**
D	Rear	30 to 46 %	n/a	38 %	n/a	11 %	n/a

Notes: All data based on two trials for each condition unless otherwise noted. System B did not warn during any of the trials on the HSTT. * Based on a single trial. ** Based on four trials.

6.1.2.1 System A Accuracy Test Results

System A's underinflation warning activated for pressure losses ranging from 8 to 23 percent. The system warned, on the average, with 7 percent less pressure loss for GVWR than for LLVW. Repeats tests of a single tire, for a given condition, were within a 3 percent standard deviation overall. In general the system warned sooner and more accurately (2 trials at each condition) for a low tire on the rear axle than for one on the front.

During testing, once the warning lamp illuminated (red light on dash), testing was stopped and the vehicle brought back to VRTC. The tires were allowed one hour to cool before setting the pressures for the next test. Then, by pushing in and holding the reset button for 5 to 6 seconds, the warning lamp cleared. To ensure that the system was re-initialized, the vehicle was driven for 10 minutes at 30 mph and 10 minutes at 60 mph before running the next leak-down sequence (Procedure for System A only). For this system, an audible warning sounded once, each time the TPMS first detected a low tire pressure condition. The tone was sufficiently loud to be heard over the hissing sound of the venting tire pressure.

6.1.2.2 System B Accuracy Test Results

For this dynamic test sequence, System B failed to warn in 5 trials on the High Speed Test Track (an illustration of the HSTT is contained in Appendix 5). Pressure was leaked down at an average rate of 1.0 psi/min from 33 psi to the minimum test pressure of 14.0 psi (58 % low). Based on these rates, the average trial lasted 18.9 minutes and the vehicle traveled 18.9 miles during the test. The TPMS calibration procedures used for these tests, which are listed at the end of this document, were specified by the service manual and did produce warnings on the Winding Road Course at pressures above 16.5 psi.

Consequently, under the definition of the test procedures (slow leak-down during constant speed, straight-line driving), System B failed to warn of significant underinflation (down to 14 psi). However, after one failed test, the vehicle was driven from the test track to another test course while a tire was still low. On the drive down the connecting road, which had a number of turns, the TPMS warning activated. After successive failed tests on the HSTT, if the vehicle was driven up and down the winding access road with the tire still low, the System B activated a warning. Therefore, the dynamic performance of this WSB system was dependent on both vehicle loading (Table 6.5) and the amount of turns encountered while driving.

The System B TPMS required that the user calibrate the system after every low tire pressure warning indication. This was accomplished by adjusting the cold inflation pressures to the placard requirements, resetting the TPMS system, then driving on the HSTT. Since no tests were performed above 60 mph, the TPMS was calibrated in two ranges, 10 minutes at 30 mph and 10 minutes at 60 mph (a one time calibration using ten minutes at each of 20, 45, and 70 mph produced the same results on the WRC as just the 30 and 60 mph speeds). It was noted that pushing the reset button toggled the driver's information display (on the dash) to indicated "TIRE PRESSURE NORMAL," which could be done with the tires still low.

When a warning did activate during testing, a triple gong audible warning sounded to alert the driver. This was sufficiently loud to be heard over the hissing of the venting tire pressure (similar to a door ajar warning tone).

6.1.2.3 System C Accuracy Test Results

System C's test vehicle was equipped with Michelin Pilot Zero Pressure (run-flat) tires. The Zero Pressure sidewalls are extremely stiff, and do not deform much, even under considerable pressure loss. Subsequently, the pressure warning levels observed for System C were quite low. The warning activation levels ranged from 14 to 41 percent below placard pressure. The system warned with, on the average, 19 percent less pressure loss for GVWR than for LLVW. System C's warning level indications had the tightest tolerance in the LLVW condition, with a standard deviation of 2 percent for both axles. In the fully laden condition, the standard deviation for the front axle was negligible (less than 1 %), but the rear axle standard deviation was 8 percent. In general the system warned sooner and more accurately (2 trials at each condition) for a low tire on the front axle than for one on the rear.

During testing, a single "gong" tone alerted the driver when the TPMS identified a low tire pressure. The gong sound was accompanied by the text "TIRE DEFECT" being displayed on the driver's information panel on the dash. The tone was sufficiently loud to be heard over the hissing of the venting air pressure. Once the warning lamp illuminated the text, “TIRE DEFECT,” the vehicle was stopped, its engine turned off, and the low tire refilled. The tires were allowed one hour to cool before setting the pressures for the next test. If the tires were refilled to the original calibration pressure, the system did not require a re-calibration. Without pushing in the reset button, the engine was restarted, and the warning lamp cleared. However, changes in inflation pressure to accommodate higher loads (GVWR) required complete re-calibration of the system.

6.1.2.4 System D Accuracy Test Results

System D’s warning activation levels ranged from 25 to 46 percent low. Time and weather constraints prevented repeats of the lightly laden test in which the right front tire was deflated and resulted in the fully laden test in which the left rear tire was deflated not being performed. Though on average, the system activated the underinflation warning with 4 percent more pressure loss at GVWR than when at LLVW. In the fully laden condition, front axle, the standard deviation was 6 percent (based on four trials at that condition). In the fully laden condition, the standard deviation for the rear axle was 11 percent (based on 2 trials).

One difference between System D and the other systems tested was that it had no audible warning with which to alert the driver that the warning had activated, just a warning lamp. On one test in bright sunlight, the driver was not aware that the factory dash-mounted warning lamp was illuminated until after a period of over 20 seconds (the warning lamp was also monitored by video camera).

Once the warning lamp illuminated, several hypotheses were explored to identify what was required to clear the warning. By stopping the vehicle and turning off the ignition, the warning lamp cleared on engine restart. If the tire was still low, the warning lamp re-illuminated after driving for about a minute at 30 mph. If the low tire was filled to match the other properly inflated tire pressures (during engine shutdown) the lamp toggled off at startup and stayed off for future driving. If the ignition was not turned off during tire refilling (such as refilling at a service station without turning off the ignition), the warning lamp eventually extinguished after ten minutes of driving on curving roads.

System D's reset procedure consisted of turning the ignition off and then on again, in essence erasing any short-term memory of a flat tire. This was suitable as long as the tires were brought back to the same cold inflation pressure the system was calibrated at and the loading was the same. System D had a reset button to push, but this caused the long-term memory to blank, erasing all tire baseline information and necessitating a lengthy calibration. This system provided no way to identify when the calibration was complete (which required 8 hours – see the calibration procedure in Appendix 3). Despite a full eight hours of calibration driving, a few trial tests were performed where no low tire pressure warnings were experienced for one tire. The lack of turns did on the HSTT did not allow the system to calibrate sufficiently. However, the system did function normally once the revised calibration procedure was implemented (Appendix 1).

6.1.2.5 WSB System Warning Status Preservation

For all four of the WSB systems, brake snubs were performed with one tire 2 psi below the system's activation pressure. After the system had warned of low pressure, brake snubs consisting of partial stops run from 60 to 20 mph were completed using the vehicle's service brakes (and the transmission in high gear). A uniform deceleration of 10 feet per second per second (0.3G) was maintained for the duration. Snubs were repeated every mile for three laps of the HSTT (or 22 miles). The snubs were meant to heat the tires and brakes enough to raise the pressure above the activation level. For all four of the WSB TPMS configurations, none of the underinflated tires acquired enough heat buildup to cause the TPMS warning to clear at the higher pressure. This indicates that the system will maintain its underinflation warning and not flicker on and off during stop-and-go driving.

6.1.3 WSB Dynamic Tests on Loose Surface

Additional tests were performed on two of the WSB TPMS equipped vehicles to determine their sensitivity to operation on a loose composition surface. The System B and System D were both tested on a 2.5 mile, winding gravel road course at speeds of 20 to 40 mph. The vehicles equipped with Systems A and C were not government-owned and could not be subjected to these tests due to concerns over damage to their paint finishes. Results for this testing are summarized in Table 6.8.

Table 6.8 – Results of Loose Surface Tests

TPMS System	Tire	Loading	Warning (psi)	Warning (% low)
System B	RF	GVWR	No warning	No warning
System B	LF	LLVW	No warning	No warning
System D	RF	GVWR	22	37
System D	RF	LLVW	31	11
System D	RF/LR	LLVW	31 / 31	9 / 9

For this test, no snubs were performed to heat the brakes and tires, as the loose surface limited the coefficient of friction to less than the 0.3 g deceleration required. The same calibration procedures that produced warnings on the WRC for System B were used to calibrate the system for tests on the winding gravel road. The right front (RF) tire was tested with the vehicle fully laden (to the GVWR), and the left front (LF) tire was tested with the vehicle in the "light" condition (LLVW). Neither condition caused the warning lamp to illuminate by the time the respective tire was deflated to 14 psi (58 % low).

The right front tire of System D was tested twice on the gravel road: once at GVWR, and again at LLVW. In the GVWR loading condition, the TPMS warned of low tire pressure at 22 psi (37 % low). In the LLVW loading condition, it warned at 31 psi (11 % low). For the gravel road tests, the TPMS was more responsive to low tire pressure in the lightly loaded condition than in the fully laden condition. This was contrary to the results on paved surfaces.

In a third test, the two tires forming the RF/LR diagonal were subjected to the slow leak-down procedure. Again the System C TPMS produced a significant underinflation warning for the two tires at 31.6 and 31.7 psi respectively (9 / 9 % low).

More testing would be needed to adequately determine the effects of the loose surface on the WSB systems sensing capabilities.

6.2 Pressure-Sensor Based TPMS

This section details the results of the PSB TPMS evaluations. Testing of the pressure-sensor based systems was conducted both statically and dynamically. The static tests had three objectives: 1) to determine the threshold warning threshold by lowering the pressure in increments, 2) to investigate the effects of temperature change on PSB systems, and 3) to determine the response time of the systems to a rapid tire deflation.

6.2.1 PSB Static Tests for System Accuracy – Pressure Dropped in 2 psi Increments

The first and third static tests were performed indoors (warm) with the vehicle raised on a lift (wheels in motion). The second static test was performed outdoors (cold) on jack stands to test the effects of temperature changes. The results of the three static tests can be seen in the following tables. Table 6.9 documents the underinflation advisory and significant underinflation warning thresholds for the six PSB systems. The thresholds are also given as a percentage of the change in pressure from the placard cold inflation pressure. For example a ΔP of 53 percent means that the advisory/warning activated 53 percent below the placard pressure.

Table 6.9 has a number of entries listed as not applicable, or "n/a". Systems E and G had only a one-stage warning that was considered to be the significant underinflation warning. Unfortunately, the electronically controlled suspension on the System E's test vehicle activated a fault code when put on a lift and placed in gear. This precluded performing the normal static tests for System E. Instead, eight outdoor tests were performed using the same 2 psi drops in tire pressure until activation occurred.

Table 6.9 – Warning Activation Pressure Thresholds

System:		E**		F		G		H		I		J	
Placard Pressure:		30 psi		30 psi		26 psi		30 psi		26 psi		30 psi	
Static Test	Driver Notification	P (psi)	ΔP	P (psi)	ΔP	P (psi)	ΔP	P (psi)	ΔP	P (psi)	ΔP	P (psi)	ΔP
1st Warm Test*	Advisory	n/a	n/a	18	40%	n/a	n/a	24	20%	n/a	n/a	26	13%
	Warning	n/a	n/a	10	67%	18	31%	14	53%	18	40%	18	40%
Cold Test*	Advisory	n/a	n/a	17	43%	n/a	n/a	24	20%	n/a	n/a	22	27%
	Warning	24	20%	9	70%	17	36%	14	54%	20	33%	18	41%
2nd Warm Test*	Advisory	n/a	n/a	17	43%	n/a	n/a	24	20%	n/a	n/a	25	17%
	Warning	n/a	n/a	10	67%	18	31%	14	53%	20	33%	17	43%
Average Advisory		n/a	n/a	17	42%	n/a	n/a	24	20%	n/a	n/a	24	19%
Average Warning		24	20%	10	68%	18	33%	14	53%	19	35%	18	41%
Average Advisory Threshold: 22 psi / 27 % Below Placard													
Average Warning Threshold: 17 psi / 42 % Below Placard													

*Each number is the average of two trials (right front and left rear tires)
** System E was original equipment on a vehicle that could not be tested on lift due to the electronically controlled suspension. The results are the average of eight outdoor trials.

Also, there were problems encountered in testing System I. The system had two levels of driver notification of underinflation, the first (the advisory) was adjustable and the second (the warning) was fixed at 20 psi. System I's display was meant to function as a stopgap aftermarket display on a system primarily intended for original equipment applications. This display had the undesirable property of rounding the pressure to the nearest 5 psi increment. The system required a "Target Pressure", which was a user adjustable advisory threshold, to be entered during configuration. System I's test vehicle had a 26 psi cold inflation pressure, which could be entered as either 25 or 20 psi (5 psi increments). If the target pressure was set at 25 psi, the system would immediately emit a warning when the TPMS was powered-up since it was rounding 26.0 psi down to 25 psi. If the target pressure was set at 20 psi, the display was quiescent for all the tires set at 26 psi. But, upon reducing the inflation pressure, the underinflation warning, fixed at 20 psi, would come on and bypass the underinflation advisory completely. So no static data was available for the underinflation advisory of System I.

On average, the underinflation advisory (three systems had one) activated at 22 psi and the significant underinflation warning (all six systems) activated at 17 psi. The activation levels of pressure-sensor based systems are independent of load or initial inflation pressure and can be easily changed by the manufacturer. Some systems compensate their advisory thresholds for changes in ambient temperature, which would affect the advisory activation threshold.

Table 6.10 documents the change in the underinflation advisory between the indoor and outdoor static accuracy tests. For all tests, the tire pressures were set in a temperature-controlled garage (approximately 70° F) to the placard "cold" inflation pressures. The two "warm" static tests were completed indoors. For the "cold" static accuracy test, the tires were set inside and then the vehicle was moved outside and allowed to cool to 30 to 50° F in the winter weather. The result was a drop in the tire inflation pressure of about 2 to 4 psi depending on the ambient temperature and the test vehicle. This meant that the first and second warm static accuracy tests were conducted at constant temperature (isothermal), but the cold static accuracy test was conducted after a large temperature drop.

Table 6.10 – Change in Underinflation Advisory Between Warm and Cold Static Tests

SYSTEM:		**F**	**H**	**J**
TEMPERATURE COMPENSATED?		**No**	**No**	**Yes**
Static Test	**Tire**	**ΔP (psi)**	**ΔP (psi)**	**ΔP (psi)**
1st warm vs. cold	RF	1.5	0.5	3.9
1st warm vs. cold	LR	0.2	0.4	4.5
2nd warm vs. cold	RF	0.5	0.5	1.9
2nd warm vs. cold	LR	0.2	0.4	4.5
	Average:	**0.6**	**0.5**	**3.7**
	Max Deviation:	**1.5**	**0.5**	**4.5**

Note: positive values indicate that the cold temperature pressure threshold is lower than at the 70 degree F set point.

For the systems with absolute thresholds, in other words no temperature compensation for the thresholds, the low pressure advisory should activate at the same pressure level regardless of temperature. As expected, the two systems without temperature compensation, Systems F and H, activated on average within 0.6 psi of the same pressure level regardless of the temperature. In comparison, the System J, in the temperature compensated mode, lowered its first warning threshold by average of 3.7 psi to adjust for the decrease in cold inflation pressure due to the drop in operating temperature. A discussion on the merits of temperature compensated warning thresholds is contained in Section 9.2.

Table 6.11 documents the change in the significant underinflation warning between the indoor and outdoor static accuracy tests.

The significant underinflation warning was considered fixed for the five systems, and was expected to activate at the same pressure regardless of temperature. Overall, the five systems subjected to indoor and outdoor testing had an average deviation of outdoor and indoor activation thresholds of 0.8 psi.

Table 6.11 – Change in Underinflation Warning Between Warm and Cold Static Tests

System:		**F**	**G**	**H**	**I**	**J**
Temperature compensated?		**No**	**No**	**No**	**No**	**Yes**
Static Test	**Tire**	**ΔP (psi)**	**ΔP (psi)**	**ΔP (psi)**	**ΔP (psi)**	**ΔP (psi)**
1st warm vs. cold	**RF**	1.5	1.5	0.7	1.0	0.1
1st warm vs. cold	**LR**	0.2	1.3	0.4	3.4	0.5
2nd warm vs. cold	**RF**	0.5	1.5	0.7	1.0	2.1
2nd warm vs. cold	**LR**	0.2	1.3	0.4	0.6	0.5
Average		0.6	1.4	0.6	0.5	0.8
Max Deviation		1.5	1.5	0.7	3.4	2.1
Max Deviation = 3.4 psi						
Non-Temperature Compensated System Average = 0.8 psi						
Temperature Compensated System Average = 0.8 psi						

6.2.2 PSB Static Tests for Response Time – Pressure Dropped Rapidly

For this test, the tire was deflated at approximately 5 psi/minute. System warning levels and response times were determined. Table 6.12 summarizes the system warning levels determined during this testing. Note that the activation levels shown in Table 6.12 may differ from those shown in Table 6.9. This is due to the response time of the systems and because some sensors automatically enter a rapid transmission mode if they sense a sudden loss of pressure, regardless of current pressure level.

Table 6.12 – Warning Activation Pressure Thresholds from Rapid Deflation Testing

(percent drop from cold inflation pressure)

System:	F	G	H	I	J
Static Test:	Advisory	Advisory	Advisory	Advisory	Advisory
	Warning	Warning	Warning	Warning	Warning
1st Warm Test*	47 %	n/a	33 %	n/a	No advisory
	83 %	9 %	59 %	50 %	52 %
Cold Test*	44 %	n/a	**	n/a	No advisory
	70 %	9 %	**	75 %	47 %
2nd Warm Test*	40 %	n/a	27 %	n/a	No advisory
	70 %	9 %	63 %	42 %	55 %
Average Warning	44 %	n/a	30 %	n/a	No advisory
	74 %	9 %	61 %	56 %	51 %
					Average Advisory Threshold: 37 %
					Average Warning Threshold: 50 %

* Average of four trials (right front and left rear tires, twice). ** Screen displayed "Lo" with RF icon indicator illuminated.

System E was omitted from Table 6.12 since the vehicle could not be tested on a lift. The display from System H never produced an audible warning during the rapid deflation outdoor test (Cold Static Accuracy Test), though System H's tire icon was continually flashing and a "Lo" message was displayed if the button was pushed. It is assumed that the display was still in the warning mode from previous tests and had not sufficiently reset before the rapid deflation segment of the Cold Static Accuracy Test.

During a rapid pressure loss, the underinflation advisory, on the average, activated at 37 percent below cold inflation pressure. The significant underinflation warning activated at an average of 50 percent below the placard pressure. While not meant to simulate a tire failure (blowout), it is promising to note that these systems will warn of a large tire puncture with more than 50 percent of the air pressure remaining. The response times necessary to produce a warning are documented in Table 6.13.

Table 6.13 – Response Time of Low Pressure Warnings to Rapid Deflation

System:	E**	F	G	H	I	J
Static Test:	Advisory	Advisory	Advisory	Advisory	Advisory	Advisory
	Warning	Warning	Warning	Warning	Warning	Warning
1st Warm Test*	n/a	80.5 sec	n/a	54 sec	n/a	-
	-	139.7 sec	8.25 sec	106 sec	47.25 sec	74 sec
Cold Test*	21.25 sec **	78.0 sec	n/a	-	n/a	-
	-	135.0 sec	7.25 sec	-	75 sec	65 sec
2nd Warm Test*	-	75.7 sec	n/a	39 sec	n/a	-
	-	133.7 sec	8.25 sec	106 sec	20.25 sec	75 sec
Average Time	n/a	78 sec	n/a	47 sec	n/a	-
	21.25 sec	136 sec	8 sec	106 sec	48 sec	71 sec
						Average Advisory Time: 63 sec
						Average Warning Time: 65 sec

*Average of four trials (right front and left rear tires, twice)
** System E's test vehicle could not be tested on lift; each response time is the average of eight outdoor trials. System E was the economy version of the manufacturer's model line. It only had one warning level and did not display pressures, though the higher end versions from that manufacturer do.

The average response times for the underinflation advisory and warning were 63 and 65 seconds, respectively. System G had the fastest average response time to the first warning, 8 seconds. System F had the longest average response time to first warning at 78 seconds. The response time to a rapid deflation relies on a number of factors. First is the relative point in time that the event occurs with respect to the next pressure update to the receiver. Second, is whether the system can sense a rapid change in pressure and enter a rapid transmit mode. Systems E, H, I, and J all enter a rapid transmit mode if a rapid change in pressure versus time is detected. The four systems with rapid transmit modes warned quicker than System G, which does not have one.

6.2.3 PSB Display Accuracy

The accuracies of the pressures displayed by the four PSB systems that displayed pressures during an advisory or warning were checked against a calibrated digital pressure gauge. The results are in Table 6.14.

The four PSB systems were as a whole very accurate. All displays were within 1 psi of the actual pressure reading.

Table 6.14 – Deviation of Pressure Displayed During Warnings vs. Calibrated Pressure Gauge

System:		**I**		**H**		**J**		**F**	
Warning:									
Static Test	**Tire**	**Advisory (psi)**	**Warning (psi)**	**Advisory (psi)**	**Warning (psi)**	**Advisory (psi)**	**Warning (psi)**	**Advisory (psi)**	**Warning (psi)**
1st Warm	**RF**	n/a	0	-1	-1	-1	-1	0	-
	LR	n/a	-1	-1	-1	0	0	0	0
Cold	**RF**	n/a	-1	0	0	0	0	0	0
	LR	n/a	0	0	0	0	0	0	0
2nd Warm	**RF**	n/a	0	-1	0	0	0	-1	-
	LR	n/a	0	0	0	0	-1	0	-1
Individual Max Deviation:		n/a	-1	-1	-1	-1	-1	-1	-1

Systems E and G had only one warning level and did not display pressures.

6.2.4 PSB Dynamic Test for Activation Levels

Three test vehicles were used to test the six PSB systems. Tests were conducted on a closed circuit test track at normal highway speeds (60 mph). Each vehicle was instrumented to record both tire air pressure and contained air temperature, in real time. A series of both fast and slow leak-down tests were performed on the six PSB TPMS to determine their activation levels. All systems were tested while the vehicles were ballasted to GVWR (the fully laden condition) to facilitate tire heating. Three things were determined during this testing: 1) Accuracy of advisory or warning thresholds; 2) Preservation of warning status; and 3) System failure effects.

6.2.5 PSB Accuracy Tests

The dynamic warning thresholds of the PSB tire pressure measurement systems were determined by leaking the tire pressure down at a controlled rate through a 0.25 inch needle valve. The valves were coupled, through heavy truck grade air lines, to rotary air couplings attached to the wheels. Two different flow rates were used during testing. To simulate a slow leak in the tire the RF and LR tires were deflated (vented) at a flow rate of 1 to 2 psi per minute (valve opened 2 turns). To simulate a mediums-sized puncture in the tire the RR and LF tires were deflated at 6 psi per minute (valve fully opened 9+ turns). The activation levels, in terms of percentage drop in tire pressure from cold inflation pressure are listed in Table 6.15. The values listed are individual test readings, as only one tire was deflated at a time for this test procedure. No simultaneous multiple tire deflation tests were performed for the PSB systems. The "Percent Loss of Placard Pressure" column reflects the relative amount of air pressure vented from the tire.

As documented in Table 6.15, Systems F, G and I occasionally failed to warn during the leak down process. For System F, a prototype, there were difficulties with signal reception. Even during static testing, the receiver would pick up some tire locations better than others. Another prototype system, System G, failed to warn in two instances. The reason for this failure is unknown. Though System I warned erratically during both the fast and slow leak down tests, through ten trials it always gave at least an advisory or a warning. The low placard pressure on the test vehicle may have caused some problems with the System I's warning algorithm.

Table 6.15 – Complete List of PSB Systems Test Results

Tire	System	Placard Pressure (psi)	Deflation Rate (psi/min)	Advisory Threshold (psi)	Percent Loss of Placard Pressure	Time Until Advisory (min)	Warning Threshold (psi)	Percent Loss of Placard Pressure	Time Until Warning (min)	Ambient Air Temp. (°F)
LF	E	32	4.9	n/a	n/a	n/a	25.4	20 %	1.3	36
RR	E	39	4.8	n/a	n/a	n/a	25.4	35 %	2.8	36
LR	E	39	1.1	n/a	n/a	n/a	25.0	36 %	12.7	38
RF	E	32	1.0	n/a	n/a	n/a	25.2	21 %	6.8	38
LF	F	30	3.6	16.3	46 %	3.8	n/a	n/a	n/a	41
RR	F	30	3.7	none @ 16.0	n/a	-	n/a	n/a	n/a	42
LR	F	30	0.8	17.1	43 %	16.1	n/a	n/a	n/a	34
RF	F	30	0.7	none @ 14.3	n/a	-	n/a	n/a	n/a	29
LF	G	26	6.2	n/a	n/a	n/a	17.5	33 %	1.4	25
RR	G	26	6.1	n/a	n/a	n/a	16.9	35 %	1.5	25
LF	G	26	1.0	n/a	n/a	n/a	17.1	34 %	8.9	26
LR	G	26	1.0	n/a	n/a	n/a	none @ 13.7	n/a	-	23
LR	G	26	1.1	n/a	n/a	n/a	none @ 13.6	n/a	-	29
RF	G	26	1.2	n/a	n/a	n/a	17.1	34 %	7.4	28
LF	H	30	3.8	24.0	20 %	1.6	14.6	51 %	4.1	30
RR	H	30	3.6	24.0	20 %	1.7	16.0	47 %	3.9	30
LR	H	30	0.8	24.6	18 %	6.8	15.4	49 %	18.3	53
RF	H	30	0.7	24.8	17 %	7.4	15.1	50 %	21.3	51
LF	I	26	7.8	22.0	15 %	0.5	19.2	26 %	0.9	58
RR	I	26	8.1	21.6	17 %	0.5	15.1	42 %	1.3	58
LR	I	26	4.1	No warning	n/a	-	16.6	36 %	2.3	39
RF	I	26	1.1	19.7	24 %	5.7	19.4	25 %	6.0	38
LF	J	30	3.9	22.8	24 %	1.8	17.0	43 %	3.3	22
LF	J	30	3.9	23.1	23 %	1.8	16.6	45 %	3.4	23
LR	J	30	4.0	23.1	23 %	1.7	17.9	40 %	3.0	24
RR	J	30	3.9	20.5	32 %	2.4	17.6	41 %	3.2	21
LR	J	30	0.9	25.4	15 %	5.1	17.3	42 %	14.1	25
RF	J	30	0.8	20.9	30 %	11.4	18.0	40 %	15.0	25

Note: All PSB systems were tested at GVWR

6.2.5.1 <u>System E Accuracy Test Results</u>

Since System E was an original equipment system, the activation threshold of the underinflation warning (single warning) was determined by the vehicle manufacturer. Empirically, the warning threshold appeared to be fixed at 25.2 psi. Placard pressure for the test vehicle was 32 psi for the front and 39 psi rear. Both the fast and the slow leak-down tests produced similar results for the front and the rear tires. The activation pressures all ranged from 25.0 to 25.4 psi. This was a tolerance of only ±0.2 psi. Since the axles required different cold inflation pressures, the corresponding 21 percent front and 36 percent rear pressure loss values do not directly correlate to the indicators from the other systems tested. The audible warning tone was sufficiently loud to be heard above the venting tire air. The dash-mounted visual display indicated the text warning "TYREPRES FRONT L," which indicated the left front tire was causing the warning. The warning was spelled with "TYRE" since this vehicle was built for the European market. Once the tire pressure was restored, pushing the reset button cleared the warning.

6.2.5.2 <u>System F Accuracy Test Results</u>

System F, a prototype original equipment system, was attached to a laptop computer to substitute for the lack of an integrated vehicle display. This system only updated every ten minutes, which made it slow to respond to the changing tire pressures. As Table 6.15 indicates, System F had reception problems for wheels on the right side of the vehicle. However, the system did provide underinflation advisories for the two left side wheels. The underinflation advisories activated 0.9 and 1.7 psi below the nominal 18 psi threshold. The underinflation warning could not be tested dynamically since its nominal 10 psi threshold was deemed too low to test safely at 60 mph, especially in a fully loaded SUV.

The ability of System F to maintain inflation pressure during driving was not evaluated, but an example of system's capabilities is documented in Appendix 2.

6.2.5.3 <u>System G Accuracy Test Results</u>

For System G, a prototype aftermarket system, special airline tees were installed adjacent to the valve stem to allow for simultaneous tire pressure monitoring by the system's externally mounted sensor and the pressure transducer feed lines. The test vehicle had a 26 psi placard pressure front and rear. The single TPMS underinflation warning was factory set at 20 psi. During dynamic (on-road) testing, the system failed to warn in two of the six trials. Both failures involved the left rear tire, which was deflated down to 14 psi with no warning. Identical procedures did produce warnings for other tires. The average warning activation pressure was 17.2 ±0.3 psi (or 33 to 35 % pressure loss).

Once the low tire pressure warning activated, it continued until the driver pushed the reset button. Then the visual warning lamp continued to blink until the tire pressure situation was corrected. Twice during the test sequence, the receiver displayed a low battery light for a tire sensor and the driver thought that this was a low tire warning. The centrally mounted warning indicators were visible on the display through the adjacent tire indicator openings, giving the driver (looking from the left side) the impression that the left front tire was causing a notification of underinflation to be presented, when it may really have been a right tire with the low pressure condition.

6.2.5.4 System H Accuracy Test Results

System H was installed on a vehicle that had a 30 psi placard pressure front and rear. The system's underinflation advisory is set by the manufacturer to activate in the 20 to 15 psi range and the underinflation warning to activate below 15 psi. System H warned of underinflation in every dynamic test. The underinflation advisories ranged from 24.0 to 24.8 psi (17 to 20 % pressure loss). The underinflation warnings ranged from 14.6 to 16.0 psi (or 47 to 51 % pressure loss). Although the advisory thresholds were at a pressure higher than expected, the tolerance on the range was tight at <±0.5 psi. The warning thresholds were within a ±1 psi band around the targeted 15 psi lower limit. The underinflation advisory was comprised of a single beep accompanied by the display flashing every other second. At the onset of the underinflation warning, the single beep changed to a distinctive double beep pattern.

6.2.5.5 System I Accuracy Test Results

System I required the "Target Pressure" to be set at installation. The underinflation advisory threshold (Target Pressure) was user defined. Since system I rounded units to the nearest 5 psi, the test vehicle's placard pressure of 26 psi left two choices for the underinflation advisory pressure, 25 and 20 psi. When the advisory was set at 25 psi, the system produced a warning immediately since

26 psi was rounded to 25 psi. The first round of dynamic test at a 25 psi Target Pressure was erratic and therefore thrown out. A second round of dynamic tests was completed with the Target Pressure set at 20 psi. Since the underinflation warning was fixed at 20 psi, it was not clear of the system would still give two notifications of underinflation or one. The results were that the system was initially quiescent, but missed an underinflation advisory during the leak-down tests. The underinflation advisory usually alerted from 22.0 to 19.7 psi (15 to 24 % low). The underinflation warnings ranged from 19.4 to 15.1 psi (25 to 42 % low). System I had an additional warning to indicate when the tire pressure was changing rapidly. This was beneficial during the leak-down process, for it warned of a degrading situation even before the underinflation advisory activated. It also warned again when the tire was being refilled. The audible warning was not very loud, and was not audible over the hissing of the venting air pressure.

6.2.5.6 <u>System J Accuracy Test Results</u>

A cold placard pressure of 30 psi was entered for System J at the time of installation. The user can set the underinflation advisory in 1 psi increments. This advisory has an optional temperature compensation mode (on by default) that compensates the underinflation advisory activation threshold for changes in temperature. The significant underinflation warning is fixed at 18 psi by the manufacturer and is not temperature compensated. System J provided both warning levels during all four tests. The default underinflation advisory threshold activated for pressures in the 20.0 to 25.0 psi (15 to 32 % loss) range. The underinflation warning activated for pressures in the 16.6 to 18.0 psi (40 to 45 % loss) range. The underinflation advisory consists of one long beep accompanied by a flashing red lamp. The display designates the tire that is low and displays the current pressure. The system alerted for the lowest tire if multiple tires were low. The underinflation warning consists of the warning light, additional warning icons, and audible tone continually turning on and off. Again, the lowest pressure and corresponding tire location were displayed on the screen.

6.2.6 <u>PSB System Warning Preservation</u>

Two methods were used to test the preservation of the underinflation notification status by the pressure-sensor based systems. The Loaded High-Speed Test was performed to determine the effect of tire heating (which raises internal pressure) on the systems preservation of the underinflation advisory. The test consisted of continuous high-speed driving with one tire deflated to 2 psi below the advisory activation level. The vehicles were loaded to gross vehicle weight and then driven for 22.5 miles (3 laps) around the HSTT at 75 mph.

In addition, at the end of the Loaded Dynamic Test, while the systems had the underinflation warning active, a series of brake snubs were performed (the same as for the WSB systems). The goal of this test was to see if the underinflation warning could be extinguished with a marginal increase in tire pressure resulting from heavy stop-and-go driving. Had time permitted, the preservation of both the advisory and the warning would have been evaluated using both the stop- and go and high-speed methods.

6.2.6.1 System E Warning Preservation Test Results

System E maintained the advisory status during the Loaded Dynamic High-Speed Test. The system also maintained the underinflation warning status during the brake snub heating segment of the Loaded Dynamic Test. The system did clear both warnings itself after the low tire was manually filled to its proper inflation level.

6.2.6.2 System F Warning Preservation Test Results

An initial pressure of 18 psi in the left rear tire was chosen for the High-Speed Test. Initially, System F's underinflation advisory was active and the receiver displayed 18 psi for the LR tire. The vehicle was then driven on the HSTT at 75 mph (with the LR tire low) for about 10 minutes, when the display updated the left rear pressure to 20 psi and cancelled the advisory. The vehicle was driven for an additional 10 minutes to see if the display changed again, but it stayed the same. System F did however maintain the underinflation warning during the brake snub sequence.

6.2.6.3 System G Warning Preservation Test Results

System G maintained the advisory status during the duration of the Loaded Dynamic High-Speed Test. The system also maintained the underinflation warning status during the brake snub heating segment of the Loaded Dynamic Test. The system did not clear either warning and required a manual reset after the low tire was manually filled to its proper inflation level.

6.2.6.4 System H Warning Preservation Test Results

System H maintained the advisory status during the duration of the Loaded Dynamic High-Speed Test. The system also maintained the underinflation warning status during the brake snub heating segment of the Loaded Dynamic Test.

6.2.6.5 System I Warning Preservation Test Results

System I cleared the advisory during the high-speed run and cleared the warning during the brake snub sequence. Enough heat was generated during the high speed driving and the brake snubs to raise the pressure to the point that the warning cleared.

6.2.6.6 System J Warning Preservation Test Results

The test pressure for the Loaded Dynamic High Speed Test was 2 psi below the activation pressure of the underinflation advisory. This pressure initially activated the underinflation warning. During the high speed driving, System J changed from the underinflation warning to the underinflation advisory. The system maintained the advisory for the duration of the test. The system also indicated a high pressure advisory (Δ +5 psi) on a tire other than the one underinflated. For this test, the tires that were properly inflated heated from around 30 to around 60°F. The underinflated tire rose from around 30 to 78° F. System J maintained the underinflation warning during the brake snub tests.

6.2.7 PSB System Failure Effects

The System Failure Test was done after static and dynamic testing had been completed to insure that the systems were properly installed and were functioning. Typically, the left front sensor was removed from the wheel to see how the TPMS responded.

6.2.7.1 System E Failure Effects Test Results

On the test vehicle, the transmitter was removed from the LF wheel, then the pressure restored. Upon moving the ignition key to the second position, the driver's information panel displayed the following warning, "TYREPRESS FRONT L." and sounded a single "gong." It had already identified a problem with the pressure in the LF tire, but it made no indication as to the nature of the problem. The test vehicle was driven on the HSTT for approximately nine minutes when the warning cleared, again making a "gong" sound. It was driven for an additional 18 miles (at 60 mph) with no new warnings. After returning to the preparation garage, the engine was turned off and the key removed from the ignition switch. After a few minutes, the engine was restarted, but the warning did not recur.

6.2.7.2 System F Failure Effects Test Results

A true evaluation of the System F's response was not possible since it was a prototype system connected to a laptop computer. The demonstration software on the computer displayed "N/S" to show that no sensor transmissions were being received for that wheel. Since System F displays "N/S" for all tires upon power-up, the ones failing to "check-in" remain in the "N/S' mode. This may not be indicative of system response in its original equipment application.

6.2.7.3 System G Failure Effects Test Results

System G unit did not identify a sensor that lost its battery completely, or that was somewhat unscrewed so the battery became disconnected.

6.2.7.4 System H Failure Effects Test Results

The left front tire sensor was removed from the wheel. The tire was remounted, filled, and the vehicle not moved for about 30 minutes. Then the vehicle was driven for over fifty miles at 60 mph on the HSTT. It did not give any TPMS warnings (a sensor failure message "SF" was expected). It did not identify that the sensor was missing from the vehicle. On a second test, the vehicle was parked and a sensor was removed from a wheel. The tire was re-mounted and refilled to placard pressure. When the vehicle was started, the display produced both audible and visual warning second level alerts (LF & LO 00). This continued for 10 minutes before the screen blanked. No more display activity was recorded for the next 30 minutes of driving (a single beep and a "SF" message were expected). However, at the end of driving, the system status button was pressed and the display read the expected "SF" and the LF icon remained illuminated.

6.2.7.5 System I Failure Effects Test Results

For System I, the sensor was removed late in the day, and the tire refilled for testing. The test was run the following morning. When the display was powered up (and the vehicle moved to activate the remaining three transmitters) the display gave correct tire pressures for the three, and indicated, "FL 00 psi" for the missing sensor tire (but no warning audible warning sounded). The display blanked after 10 seconds. The test vehicle was driven on the HSTT at 62 mph. The driver manually prompted the display (pushed the “tire” button) every 4 to 6 minutes to see if the display had changed. The display values followed the gradual changes of pressures of the three “transmitting” tire, but still showed, “FL_00_” for the “missing sensor” tire. After driving approximately 40 minutes, a double beeping alert sounded, once a second, for 10 seconds. The loss of sensor data warning “FL_Ser” flashed (once a second) on the display and continued while the vehicle was refueled and driven back to the preparation garage. It was noted that although the audible warning was audible over the sound of a low volume radio station, it was still hard to hear.

6.2.7.6 System J Failure Effects Test Results

On System J, when the LF sensor was removed from the wheel, the screen powered up blank (no messages), but did indicate that it remembered that four tires should be out there (displayed four tires on car picture). The steady red light was illuminated, indicating that the receiver had detected a possible problem. As soon as the vehicle was moved, the display began to flash the flat tire symbol and pressure of 0 psi. The vehicle was driven on for 14 minutes when the screen updated to a “delta” & “E1” warning on the LF tire, indicating the sensor problem. Once the sensor was reinstalled, System J automatically recognized the return of sensor signal and reset the system to normal status.

7.0 HUMAN FACTORS ASSESSMENT OF EXISTING TPMS DRIVER INTERFACES

7.1 Method For Examination of TPMS Driver Interfaces

Driver interfaces for existing tire pressure monitoring systems were examined. Visual and audible information displays were characterized in terms of the following:

- Type of information displayed (status, tire pressure, advisory, warning, and system failure)
- Level of detail of information presented ("a tire is low" vs. "left front tire is low" vs. "left front tire is low by 6 psi")
- Method of information display (display type, characteristics)
- Conditions of information display (message threshold, information presentation interval, message timing)
- Purpose and type of manual controls (if any)

Information presentation methods were observed through static and dynamic tests in which low tire pressure messages were triggered for each system. Digital still photos and video were recorded to document interface features and to capture warning presentation methods. System documentation provided by the tire pressure monitoring system manufacturer or by the vehicle manufacturer (for OEM systems) was reviewed to better understand their function, operation, and system features.

7.2 Overview of Existing Systems

Table 7.1 summarizes the characteristics of commercial and prototype TPMS driver interfaces examined. Details are provided regarding number of warning levels, type of information presented, method of information presentation, and system features.

Table 7.1 – Driver Interface Characteristics for Tire Pressure Monitoring Systems

System	System Status Information (Sensor Failure, Low Receiver/ Transmitter Battery)		Low Pressure Advisory		Underinflation Warning		Tire Temp Warning		Tire Specific Information	Manual Pressure Check	System Reset Button
	Visual	**Auditory**	**Visual**	**Auditory**	**Visual**	**Auditory**	**Visual**	**Auditory**	**Visual**	**Control**	**Control**
A	ISO tire pressure icon (K.11), yellow	Single beep	n/a	n/a	ISO tire failure icon (K.11), red	Single beep	n/a	n/a	n/a	n/a	Modified ISO icon K.10 on dash
B	ABS light, “TIRE PRESSURE NORMAL”	3 “gongs”	n/a	n/a	“Check Tire Pressure”	3 “gongs”	n/a	n/a	n/a	n/a	“Gage Info” button toggles options
C	Red LED text, “TIRE CONTROL INACTIVE”	Single beep	n/a	n/a	Red LED text, “TIRE DEFECT”	Single beep	n/a	n/a	n/a	n/a	“RDC” button on dash
D	For malfunction, ISO icon either will not light or stays lit	n/a	n/a	n/a	ISO icon K.10	n/a	n/a	n/a	n/a	n/a	Button labeled with ISO icon (on lower dash)
E	Unknown	n/a	n/a	n/a	Red LED text, “TYREPRESS (front/rear) (L/R)”	Single “gong”	n/a	n/a	Yes	n/a	“RDC” button on dash
F	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
G	Only low battery indication (“LOW BATT”)	Unknown	n/a	n/a	“Low Tire” red text; low tire flashes red, both tires on other axle light steady red?	Repeated beep	n/a	n/a	Illuminates tire on vehicle display	n/a	“reset”; clears warning if pressure is OK
H	“OK”, “BAT LO” for low battery”, “nP” for no pressure, “SF” for sensor failure	Single beep	Alternates between “Lo” and “(psi value)” every second for <20 psi, Tire also illuminates on vehicle outline display	Single beep once every 10 seconds	“Lo” and psi for <=15	Double beep once every 10 seconds	n/a	n/a	A tire lights upon vehicle display; Tires are labeled “RF”, “LF”, “RR”, “LR”	Provides actual psi value ±1 psi	Single button, no label, not sure if it resets
I	Lists tire and error messages including: “Ser”, “Por”, “Fer”, “dEr”, “EEr”, “Err1", “Err2", “Err3", “Err4”, “_ER2”	Beeps for about 10 s if a problem is detected.	For decreasing pressure, lists tire indication and “PEr”; for pressure below target, lists tire indication and “UEr”	Repeated double beep (every second for 10 s)	“Fr_Lo_” “FL_Lo_” “rR_Lo_” “RL_Lo_”	Repeated double beep (every second for 10 s; repeats cycle every 10 min)	Yes	Yes	Indicates “Fr”, “FL”, “rR”, “rL”	Gives actual psi value ± 5 psi	n/a. (Has toggle buttons for and mode only)
J	Steady red light if no signal is received from a tire; changes to flash after 15 min.	After 15 min. of no signal from a tire, the system beeps	Deviation from required psi; red light bar flashes; button press stops flashing, red bar remains lit	One long beep	psi; red light bar and flat tire icon flash; button press stops flashing, red bar remains lit	Continuous single beep once per second	Yes	Yes	Lights up tire on vehicle display	Provides actual psi to nearest 1 psi	n/a (Has toggle buttons for and mode only)

7.3 Details and Critique of Individual Systems

This section presents the warning methods of each system and some of the advantages and disadvantages of some of those methods.

7.3.1 System A

System A provided indication of significant tire underinflation using the ISO icon for "tire failure" (K.10). This symbol was located near the gauge cluster amongst other similar icons, as shown in Figure 7.1. An auditory warning coincided with presentation of this message as described in Table 7.1.

Figure 7.1 – Visual Warning of System A (top right corner)

Later comprehension tests show that drivers do not recognize this symbol as referring to a failure condition. The use of this symbol (tire cross-section with exclamation point) to alert the driver to the non-failure condition of tire underinflation is somewhat inappropriate based on the ISO standard.

The icon illuminated with the color red to show underinflation and the color yellow to show a system malfunction condition. This appropriate use of color was a good feature that was not seen in most other systems.

This system also featured a reset button located in the center area of the dashboard. The button was labeled with the text "RDW". Without reading the vehicle owner's manual, a driver may not realize that this button is used to reset the tire pressure monitoring system rather than to turn it on, for example. A text label incorporating the word "reset" could provide clarification.

7.3.2 System B

The System B provided a visual warning when a tire became significantly underinflated. This visual warning consisted of a green text message reading "CHECK TIRE PRESSURES," as pictured in Figure 7.2. When this message was presented, the "GAGE INFO" button could be pressed to see an additional message, "TIRE PRESSURE LOW: CHECK TIRES." An auditory warning coincided with presentation of the initial message as described in Table 7.1. This system required the use of a reset button to prompt calibration of the system after a change (such as tire rotation).

Figure 7.2 – Visual Warning of System B

7.3.3 System C

System C provided visual indication of low tire pressure using red LED text stating "TIRE DEFECT" as shown in Figure 7.3. An auditory warning coincided with presentation of this message as described in Table 7.1.

Figure 7.3 – Visual Warning of System C

This system also featured a reset button located to the right of the steering wheel. The button was labeled with a modified version of ISO icon K.11, as shown in Figure 7.4. This symbol contained the exclamation point indicating failure (as did the visual warning icon), but also contains a triangle presumably indicating "hazard". Use of multiple symbols for the same system within a vehicle may cause confusion. A text label stating, "reset" to complement an icon used to label the button, could provide clarification.

Figure 7.4 – Reset Button Label for System C

7.3.4 System D

System D used the ISO symbol for "tire pressure" (K.11) to indicate conditions of significant tire underinflation. This symbol was located near the gauge cluster amongst other similar icons, as shown in Figure 7.5. A reset button for use in prompting re-calibration of the system after tire rotation or tire replacement was present on the left side of the dashboard under the steering wheel.

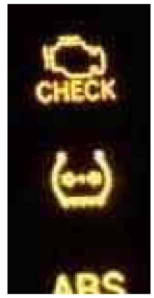


Figure 7.5 – Visual Warning of System D (Center Icon)

7.3.5 <u>System E</u>

System E provided visual indication of low tire pressure using red LED text stating "TYREPRESS (FRONT/REAR) (L. / R.)". Figure 7.6 illustrates the system indicating that the pressure in the left front tire is low. The European spelling of tire ("tyre") was appropriate for this European version of this particular make/model. We assume that the version intended for use in the American market would use spellings appropriate for that market.

Figure 7.6 – Visual Warning of System E

7.3.6 <u>System F</u>

This system was a prototype. Its driver interface was still under development and thus was not available for examination.

7.3.7 <u>System G</u>

The driver interface for System G consisted of a dashboard-mounted display featuring an outline of a car. This display featured illuminating tires as well as a "LOW TIRE" message for use in indicating the condition of low tire pressure. An auditory warning coincided with presentation of the visual alert as described in Table 7.1.

Figure 7.7 shows System G driver interface un-powered. Figure 7.8 shows this system's method of providing a visual warning for the left rear tire. As can be seen, that although only the left tire had low pressure, light leaking around the low-tire indicator made it appear that both front tires were also illuminated. This method of presenting a low tire pressure warning is likely to confuse drivers by making them unsure which tire is low and frustrate them by making them have to check the pressure of multiple tires to determine which one is low.

Figure 7.7 – Driver Interface of System G - Un-powered

Figure 7.8 – Visual Warning of System G

7.3.8 System H

System H provided indication of low tire pressure using an LCD display that was integrated into the rearview mirror. Figure 7.9 shows only the bottom portion of the mirror housing which contained the visual display and selector button. This display provided visual warning of tire underinflation in terms of the specific tire, or tires, that were underinflated as well as the current pressure value(s). An auditory warning coincided with presentation of the visual warning message as described in Table 7.1.

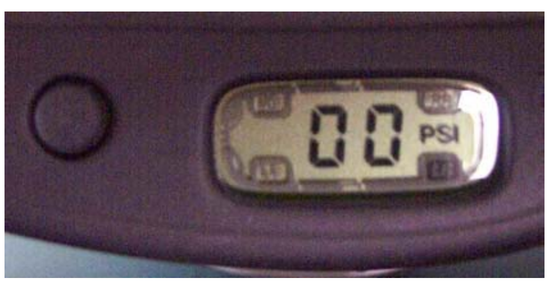


Figure 7.9 – Driver Interface of System H

During testing, several persons observing the system misunderstood the visual display by not realizing it represented a vehicle facing left and thus thinking a warning was for a different tire than it actually was. This suggestion agrees with the recommendation of ISO Standard 2575 which states:

> "4.4 …If a symbol shows a vehicle or parts of a vehicle in a top, plan view, a vehicle moving from bottom to top on the symbol shall be assumed."

7.3.9 System I

The driver interface for System I tire pressure monitoring system consisted of a dashboard-mounted display featuring red LED text. Text messages were used to provide indications of specific tires being underinflated as well as system malfunction conditions. Figure 7.10 shows this system's methods of providing a visual warning for the left rear tire ("rL_Lo_"). An auditory warning coincided with presentation of the visual alert as described in Table 7.1.

The text codes presented by this display were frequently difficult to decipher and confusing. One error message was seen during testing that was not defined in the user manual.

Figure 7.10 – Driver Interface of System I

7.3.10 System J

In this evaluation the optional Full Function System J Display was evaluated rather than the basic system. The driver interface for System J consisted of a dashboard-mounted display featuring a green backlit LCD panel. This display contained an outline of a vehicle as well as a numeric value used to present tire pressure and temperature information. Low tire pressure warnings were presenting by illuminating a flat tire symbol on the LCD panel as well as illuminating (on the vehicle outline display) the tire that was low. A red LED "alarm light" bar above the LCD display also illuminated to emphasize the presence of a warning. A numeric display presented tire pressure and temperature values in either English or metric units. A triangular "alert indicator" illuminated any time the actual pressure of the tire deviated from the required pressure by more than the preset (driver selectable) level. This alert indicator also illuminated when the temperature from a transmitter exceeded the programmed setting. Figure 7.11 shows this display indicating a 0 psi value for the left rear tire (left image) and a significant underinflation warning for the right front tire (right image). An auditory warning coincided with presentation of the visual warning information as described in Table 7.1. This system could accommodate up to 20 sensors for monitoring of up to 20 tires at once. However, the driver display could only present warnings for 10 sensors on the screen. For a vehicle with more than 10 tires, the driver would have to press a button to switch the display between the first 10 tires and the remaining tires.

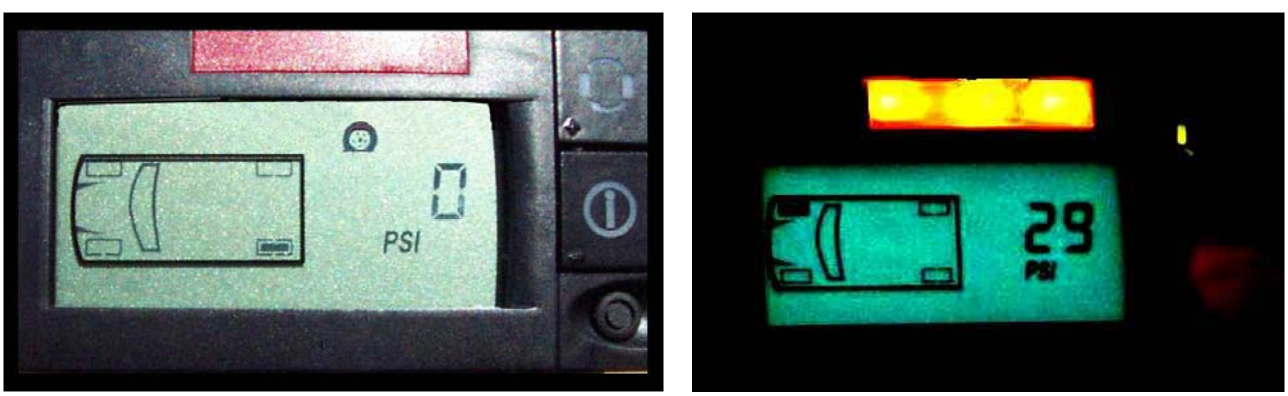


Figure 7.11 – Driver Interface of System J

As stated previously, ISO recommends that in using a top-view vehicle symbol, as in this system, the front of the vehicle should be pointed upward, as this may increase the likelihood that the driver will recognize the correct wheel that the warning is associated with. In addition, this display was found to be difficult to read outdoors due to glare.

7.4 Discussion of Tire Pressure Information Presentation Issues

7.4.1 Type of Information Displayed

All systems provided visual indication of significant underinflation of one or more tires. All but one system provided an audible signal to accompany the visual indication of significant tire underinflation. Some systems also provided an underinflation advisory for less severe conditions of underinflation (as defined by the manufacturer).

7.4.2 Level of Detail of Tire Pressure Information Presented

Various levels of detail of tire condition (e.g., "a tire is low" vs. "left front tire is low" vs. "left front tire is low by 6 psi") information were seen in the systems examined. All six of the PSB systems had the capability to inform the driver of low inflation for one or more specific tires. This information was provided either graphically, through illumination of a tire on a vehicle illustration, or textually using codes to refer to a specific tire (e.g., LR for left rear). Tire-specific inflation information may be useful since the driver would be able to identify the underinflated tire(s) without having to check all four tires.

7.4.2.1 Presentation of Actual Pressure or Relative Pressure Information

If a TPMS has the ability to compensate tire pressure readings according to ambient temperature, relative pressure information can be provided to the driver. Drivers could be presented with the exact value of psi offset from the recommended pressure at any point in time. Many vehicles currently on the market provide the driver with an indication of the ambient temperature outside the vehicle. This information could be fed into the TPMS allowing pressure readings to be adjusted according to outside temperature, which should result in more accurate inflation levels.

Temperature compensation in a TPMS is a feature that may be most helpful in preventing driver confusion relating to the operation of the system. For example, it is possible that a driver could leave their home with their vehicle's tire pressure at a somewhat underinflated level (say 4 psi low), but after driving for some time, the tire is heated therefore increasing the pressure within the tire to the recommended pressure. However, with the tire heated, the value of the recommended pressure, given the tire heating, is now actually insufficient. If the vehicle were equipped a TPMS that compensated for temperature, the system would initially tell the driver that the tire was 4 psi low and would continue to report that the tire was 4 psi low even after driving for some time and heating the tire. Thus, providing temperature compensation as a feature of the TPMS will provide more accurate information to the driver and may prevent confusion caused by changes in tire pressure readings with tire heating.

Additional information regarding temperature compensation is provided in Section 9.2.

7.4.3 Levels of Warnings

In addition to providing an underinflation warning, systems can provide an additional service to the driver by alerting them when the tire pressure is low (but not significantly underinflated). This would give the driver more opportunity to address the situation and prevent excessive wear on the tire. These low-pressure advisories, however, should not be annoying to the driver (e.g., possibly by minimizing the use of auditory signals). The alerts should be easily distinguishable from the underinflation warnings. An automobile manufacturer that has experience with TPMS recommended a 6 psi margin between placard pressure and the underinflation advisory to limit false warnings.

Alerting a driver to the condition of overinflation may also be beneficial. Overinflation causes excessive wear to the center of the tread pattern and shorter tire life. This condition is not known to be dangerous; however, avoiding overinflation and ensuring expected tire life would increase consumer satisfaction. Since overinflation is not known to present the same danger that underinflation does, a different visual display should be used to indicate overinflation.

7.4.4 Method of Tire Pressure Information Display

The system should communicate the condition of tire underinflation clearly. The system should continue to provide alerts to the driver at intervals to ensure that the situation is remedied within a reasonable time frame. A visual alert may remain constant until a condition of underinflation is remedied; however, auditory signals should not be continuous in order to not become a nuisance.

Presentation of the visual warning may take various forms. Two specific methods of warning communication are described below.

7.4.4.1 Icon for Communication of Tire Underinflation

ISO recommends the use of an exclamation point to indicate failure as evidenced by a number of icons contained in ISO Standard 2575 (2000). Since tire pressure monitoring systems do not indicate failure of a tire, only low pressure, it seems inappropriate to use a failure symbol as a method of visual warning of tire underinflation. Consistency of the presentation of visual warnings for a new system, such as TPMS, is important to assist in drivers' familiarization with the system and the type of information they present. Section 8.3 discusses use of different icons to present visual warnings for tire underinflation and presents some recommendations.

7.4.4.2 Vehicle Display Orientation

Although communicating that a tire is low may not be critical information that requires a quick response from the driver, providing information in a format that is not confusing to the driver is still important. This leads to the suggestion that if the system has a visual display consisting of a vehicle outline with indications of tire locations for provision or low pressure warnings, this vehicle should be oriented "hood up" so as to prevent confusion as to which tire has a problem. This suggestion agrees with ISO Standard 2575 (2000) which states, "…If a symbol shows a vehicle or parts of a vehicle in a top, plan view, a vehicle moving from bottom to top on the symbol shall be assumed."

7.4.4.3 Auditory Warnings for Tire Underinflation

Overall, 3 of the 10 systems examined provided auditory low-pressure advisories and 8 provided auditory warnings of underinflation. These auditory signals were generally useful and helped ensure that the driver would notice the advisory or warning when it was presented (in some cases, visual only signals were not noticed by the driver during testing). The use of short tones rather than continuous signals was considered to be a favorable attribute of most systems examined.

Auditory signals, although important to the communication of warnings, were not investigated further to develop a specific recommendation (as was done with icons) due to time constraints. As a result, recommendations for specific characteristics of preferred auditory warnings for TPMS are not provided here. Auditory warnings, if implemented, should be used for conditions requiring immediate attention from the driver in an effort to avoid them being perceived as a nuisance.

7.5 Discussion of Issues Regarding Other Types of TPMS Information and Interface Issues

7.5.1 Tire Temperature Information

Two of the six PSB systems also provided an indication of when a tire exceeded its acceptable operating temperature. Tires can reach higher temperatures when they are underinflated, thus in some cases, warning of high temperature is redundant information. However, temperature information can be important in cases where the tire is properly inflated but the vehicle is loaded more heavily than the tire is designed to accommodate. The excessive tire heat that may be generated from overloading can contribute to tread separation. Thus providing tire temperature alerts can be a useful safety feature.

7.5.2 System Status Information

All systems provided some indication of when the system was not functioning properly due to a malfunction or other problem. Some systems that used a dashboard icon as a sole visual warning display presented both warnings and system malfunctions in the same manner. To prevent confusion, it is best to present these two conditions (malfunction and warning) by distinctly different methods (e.g., different display color). Additional features that would be helpful to the driver would include providing visual indication that the system is functioning properly as well as visual indication of fault conditions.

7.5.3 Manual Controls

Some TPMS examined contained controls for programming and resetting the system (e.g., after tire rotation). Reset controls should be clearly labeled with a recognizable symbol or text and do not need to be positioned prominently on the dashboard since they will be infrequently needed or used. Similarly, programming controls should only be needed when setting up the system or making a configuration change. However, some systems provide the driver with the ability to check the status of each tire in turn by pressing a button repeatedly to switch between the tires. The ability to check a tire's status on command may be useful to drivers and provide them with extra comfort and assurance in the event that a change in the feel of the vehicle makes them curious as to the condition of the tires.

7.6 Discussion of TPMS Operation Issues That Relate to the Driver

7.6.1 Is Static Pressure Measurement Needed?

Some TPMS do not have the ability to provide tire pressure readings while the vehicle has been started but is still stationary. If all tire sensors in a TPMS have the ability to statically determine tire pressure and warn of low pressure before the vehicle is moving (i.e., ignition triggered instead of rotation triggered), the situation of someone driving more than a mile down the road on an almost flat tire before a system starts transmitting can be avoided.

7.6.2 Need for Automatic Sensor Location and Automatic Setup

In order to provide tire-specific information (e.g., the left front tire is low), the TPMS needs to be able to distinguish between the different tire locations. This means that when the tires are rotated, the TPMS will either have to detect the new locations of the pressure sensors or be told of those locations. Relying on drivers to correctly program their TPMS each time the tires are rotated may be asking too much. Systems that automatically recognize the new locations of sensors and require only minimal, if any, driver interaction to set up the system would be most convenient for the consumer and could promote proper system operation.

7.7 Driver Interface Summary

This section examined the driver interfaces of several TPMS. The following recommendations are a summary of the findings discussed earlier:

- The telltale icon must be one that the driver will recognize
- If a vehicle icon is used, the vehicle's front end should point upward
- There should be a system malfunction indicator
- The system's reset button should be labeled as "reset"
- If text messages are used, they must not be abbreviated to the point at which they cannot be understood by the driver
- Auditory signals are useful in presenting urgent information, but must not become nuisances

The following suggestions are features that would be useful to the driver:

- Tire-specific information that would let the driver know which tire is low
- A way to individually display the pressure at each tire
- An alert when the tire is running hot

Most of the variation seen between interfaces examined in this effort was confined to aftermarket systems. Original equipment systems mainly consisted of icon or text displays for presentation of visual warnings. Since the focus of this work is to provide recommendations for original equipment systems, the following section focuses on the selection of an appropriate visual warning for use by an OEM TPMS to alert drivers to the condition of significant underinflation. Despite the fact that these recommendations are intended for original equipment TPMS, aftermarket systems could also benefit from this information.

8.0 <u>INVESTIGATION OF TPMS ICONS</u>

To support development of a minimum performance standard for TPMS, which would include specification of an icon to warn drivers of significant tire underinflation, existing ISO icons and alternative icons were examined for their ability to communicate this message.

8.1 <u>Description of Existing ISO Tire Pressure Symbols</u>

ISO Icons K.10 and K.11 (shown in Table 8.1) are currently used in some vehicles to alert the driver that one or more tires on the vehicle are significantly underinflated. The symbols include a tire profile (cutaway view of a tire) and a message relating to tires, e.g. tire pressure, tire failure, etc.

Table 8.1 – ISO Tire Pressure Icons Tested

ISO Icon	
Tire Pressure (K.11)	
Tire Failure (K.10)	

Investigation of the history of the ISO tire icons did not produce any indications that the icon had been tested for comprehension. It is possible that the tire symbol was borrowed from the German DIN standard. Informal reactions of numerous persons to these icons suggest that they are not well understood. The perspective of a tire image as portrayed in the icons is not likely to be readily visualized and thus understood by the average driver. Therefore, a study was performed to assess the comprehensibility of the two ISO tire icons.

8.2 <u>Methods for Development and Testing Alternative Tire Pressure Icons</u>

In an effort to develop recommendations for methods of presenting tire pressure warning information, NHTSA examined existing ISO icons and investigated several alternative icons for "tire pressure". This research focused on testing icons for alerting drivers to the condition of significant tire underinflation, which requires immediate attention, but assumed that this icon would also be used as part of the lower-level advisory warning as well. The possibility of providing tire-specific underinflation information was not ruled out. The remainder of this section documents these efforts to assess methods of providing tire underinflation information to drivers through use of a visual symbol. Auditory signals, although important to the communication of warnings, are not discussed in this paper.

8.3 <u>Identification of Alternative Tire Pressure Warning Icons</u>

An examination of the driver interfaces for existing tire pressure monitoring systems found a number of different methods in use for providing information to drivers regarding tire underinflation. Visual indications of significant tire underinflation were provided using in some cases K.10 and K.11 (both to indicate low tire pressure, not tire failure), red LED text (e.g., "tire defect", "Lo", "Fr_Lo_"), and a few different types of vehicle images with the ability to indicate that a specific tire, or tires, was underinflated. Some systems provided two levels of warning, an indication of low tire pressure and an indication of significant underinflation.

Candidate icons for use in presenting tire pressure warning information were developed through informal production tests in which research staff produced drawings to represent tire underinflation, examination of existing systems, and review of relevant literature. Four icon versions were developed which all made use of the side image of a tire mounted on a wheel, as shown in Table 8.2. Icon versions "Flat 1" and "Flat 2" were variations of an icon presented in Green (1979), which differed only in the way that the flat part of the tire and ground were depicted. [12] Each of the four versions was drawn with three different wheel designs to permit assessment of which would be most recognizable as a wheel. Another icon was developed which consisted of a top view line drawing of a vehicle with one tire shaded (indicating a warning associated with that tire). These alternative icons were tested along with the ISO icon K.11 (version with filled in arrows) (ISO 2575) representing "tire pressure". [13] ISO icon K.10, representing "tire failure" was also tested to assess whether in comprehension tests it could be comprehended and distinguished from K.11. An existing dashboard icon that indicates engine (ISO F.01) was used as a baseline, as shown in Table 8.3.

Table 8.2 – Alternative Tire Pressure Icons Tested

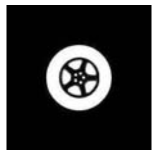
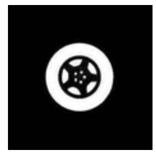
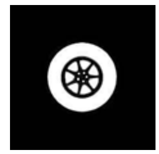
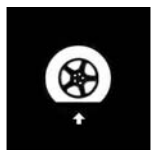
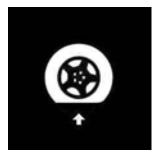
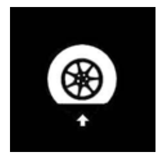
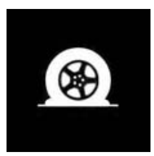
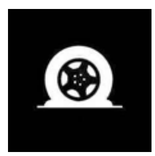
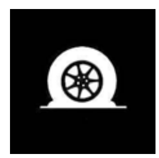
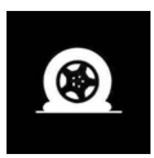
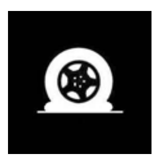
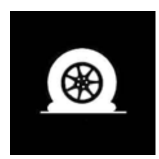
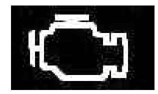
Icon Version	Wheel 1	Wheel 2	Wheel 3
Tire			
Flat tire w/arrow			
Flat 1			
Flat 2			
Vehicle			

Table 8.3 – ISO Engine Icon Used as a Baseline

ISO Icon	
Engine (F.01)	

8.4 <u>Comprehension Test</u>

Participants in the comprehension test were 120 employees of the Transportation Research Center Inc. They consisted mostly of entry-level test drivers, but also included office employees, technical staff members, and mechanics, none of whom would be expected to have any specific technical knowledge that would influence their responses. Participants were given a sheet of letter size paper containing images of two icons, including one of the 15 tire pressure icons and the ISO engine icon. Also printed on the sheet was the instruction to look at the pictures and then fill in the blanks in the statements printed immediately below each icon. The statements used were adapted from a study by Green (1993). [14] The statement consisted of the following:

> "This image has just appeared on your vehicle's dashboard.
> It is a warning for ______________________________."

Icons used were black and white and identical to those shown in Table 8.2 and Table 8.3. ISO tire icons as printed were approximately 28 mm by 28 mm. All alternative tire pressure icons as printed were approximately 33 mm by 33 mm. The printed dimensions of the engine icon were 25 mm wide by 15 mm high.

The percentage of correct responses was calculated for each icon. Correct responses were also examined as a function of icon version and wheel type. Trends in incorrect responses to particular icons were summarized. Patterns in phrasing used by respondents in the free response task were also assessed.

Correct responses were given a value of one and incorrect responses a value of zero. Responses for the ISO engine icon were considered correct if they contained the word "engine" or "motor". Given that the realm of tire-related problems is quite limited (i.e., tire wear, which is visually observable, and tire inflation issues, which may not be visually observable depending on tire design and degree of underinflation), responses to icons intended to communicate tire underinflation were given one point if they contained the word “tire”. Tire icon responses containing the word “wheel” but not the word “tire”, were given half of one point.

8.5 Results of Comprehension Test

Results of comprehension testing of the 16 symbols are provided in Table 8.4 and Table 8.5. Respondents showed near perfect (95 percent) comprehension results for the existing engine icon. Recognition percentages for the ISO tire pressure and tire failure icons were the lowest of the 16 icons tested, 37.5 percent and 25 percent, respectively. All of the 13 proposed alternative tire pressure icons had better comprehension. Percent correct observed for the icons based on tire images ranged from approximately 62 percent to 100 percent (6 of the 12 had 100 percent comprehension). The percentage of correct responses associated with the vehicle image icon was 81 percent.

To assess which of the icon versions and wheel types had the best comprehension, the number of correct responses for icons was summarized by these factors. The row totals in Table 8.4 contain the number of correct responses for tire image based icons by icon version. The column totals contain the number of correct responses for tire image based icons by wheel type. The icon version “Flat 1” had the best comprehension results of all the icon versions. These data also show “Wheel 2” to have better comprehension than the other two wheel types.

Table 8.4 – Comprehension Test Results by Icon, Results for Wheel-based Icons

	Wheel 1		**Wheel 2**		**Wheel 3**		**Total**	
Icon Version	**Points**	**Percent Correct**	**Points**	**Percent Correct**	**Points**	**Percent Correct**	**Points**	**Percent Correct**
Tire	5.5/8	69 %	8/8	100 %	5/8	63 %	18.5/24	77 %
Flat tire w/arrow	7/8	88 %	8/8	100 %	6/8	75 %	21/24	88 %
Flat 1	8/8	100 %	8/8	100 %	7/8	88 %	23/24	96 %
Flat 2	8/8	100 %	8/8	100 %	5/8	63 %	21/24	88 %
Total	28.5/32	89 %	32/32	100 %	23/32	72 %	83.5/96	87 %

Table 8.5 – Comprehension Test Results - Baseline, ISO icons, and Vehicle Top-view

Icon	**Points**	**Percent Correct**
Engine	114/120	95 %
ISO K.10	2/8	25 %
ISO K.11	3/8	38 %
Vehicle Top-view	6.5/8	81 %

A variety of incorrect responses were observed for the icons tested. Examples of incorrect responses in the interpretation of the ISO icon for tire pressure included “airbag”, “light out”, “disengaged gearshift”, and “connection check (fuses)”. Similar problems were found with the interpretation of the ISO tire failure icon, including responses such as “traction control”, “check engine”, “low oil”, and “don’t know”. Incorrect responses for Wheel 1 included “brake problems”, “electrical”, and “wheel”. Wheel 3 was predominantly mistaken to represent something steering related (such as “power steering” or “steering problem”); however, it was also mistaken to indicated “brakes”, “wheel problem”, “lights”, and “turbo”.

Table 8.6 and Table 8.7 summarize response phrases obtained by wheel type and icon version, respectively. Overall, "flat tire" was the phrase given most frequently (35 %) in response to tire pressure icons tested. However, when examining responses to the two ISO icons, most of the responses fell into the "other" category (i.e., terms not relating to tire, wheel, etc.). "Flat tire" was the predominant response given for the "Flat Tire with Arrow" icon (54 %), the "Flat 1" icon (75 %), and the "Flat 2" icon (35 %). For the vehicle icon, the most commons responses were both "flat tire" and "low tire pressure" which received 25 percent. "Flat tire" was also the most frequent response for each of the three wheel types. In all, the alternative icons appear to do a better job of communicating the idea that a condition relating to tire inflation warrants the driver's attention than does either of the ISO icons.

Table 8.6 – Summary of Percent Response Phrases by Wheel Type (rounded)

Response Phrase	**Wheel 1**	**Wheel 2**	**Wheel 3**
Flat tire	39 %	45 %	42 %
Low tire pressure	8 %	20 %	3 %
Other	6 %	0 %	22 %
Low tire	3 %	9 %	9 %
Tire(s)	9 %	13 %	0 %
Wheel	9 %	0 %	13 %
Tire problem	3 %	3 %	5 %
Tire pressure	9 %	3 %	3 %
Low air	9 %	0 %	0 %
Check tires	0 %	3 %	3 %
Tire inflation pressure	3 %	0 %	0 %
Underinflated tire	0 %	3 %	0 %
Total	100 %	100 %	100 %

Table 8.7 – Summary of Percent Response Phrases by Icon Version, Including ISO Tire Icons

Response Phrase	**ISO Tire**	**Tire**	**Flat Tire w/Arrow**	**Flat 1**	**Flat 2**	**Vehicle**
Flat tire	0 %	4 %	54 %	75 %	35 %	25 %
Low tire pressure	6 %	17 %	13 %	2 %	10 %	25 %
Other	69 %	17 %	8 %	0 %	13 %	13 %
Low tire	13 %	0 %	4 %	8 %	17 %	0 %
Tire(s)	0 %	25 %	0 %	4 %	0 %	13 %
Wheel	0 %	15 %	8 %	6 %	0 %	13 %
Tire problem	0 %	15 %	0 %	0 %	0 %	13 %
Tire pressure	6 %	0 %	4 %	4 %	13 %	0 %
Low air	0 %	0 %	4 %	0 %	8 %	0 %
Check tires	0 %	4 %	4 %	0 %	0 %	0 %
Tire inflation pressure	0 %	4 %	0 %	0 %	0 %	0 %
Underinflated tire	0 %	0 %	0 %	0 %	4 %	0 %
Punctured tire	6 %	0 %	0 %	0 %	0 %	0 %
Total	100 %	100 %	100 %	100 %	100 %	100 %

8.6 Conclusions Regarding Tire Pressure Icons

Results of the first comprehension test showed that all of the icons proposed as alternatives to the ISO tire pressure icon were found to communicate at least some degree of tire inflation condition much better than the ISO icons. All of the alternative icons had recognition rates that were at least two times better than those of the two ISO icons. Six of the alternative icons received 100 percent comprehension of their tire underinflation message in this small sample test. Considering results of the most recognizable wheel type combined with the most recognizable icon version, one of these six icon appears as being the most likely to be associated with the best comprehension rate (shown in Figure 8.1).

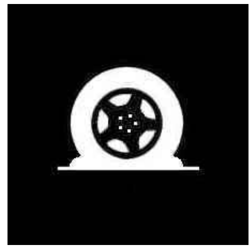


Figure 8.1 – Icon Most Recognizable As an Indicator of Tire Underinflation (Wheel 2-Flat 1).

Based on these results, it was suggested that alternatives to the existing ISO be considered for use in alerting drivers to low tire pressure. Specifically, it is suggested that the icon “Wheel 2-Flat 1” be considered for incorporation into the minimum performance specification. It is likely that use of this icon will result in better recognition of the low tire pressure warnings and as a result, better compliance with the warning’s suggestion that the driver should add air to the tire at their next opportunity.

The authors found it interesting that wheel design, which was thought to be a relatively minor component of the icon, significantly influenced comprehension. Indeed, the results indicate that the design of the wheel was more influential than the icon version in determining comprehension.

8.7 <u>Alternative Tire Pressure Display Option</u>

Another icon receiving high recognition ratings (81 %) was a “vehicle” icon consisting of a top-view line drawing of a car, as shown in Figure 8.2. Many vehicles already contain a display of this type to indicate to the driver that a door is ajar or fuel is low. This type of vehicle display could also be implemented in vehicles for the presentation of low tire information. Use of this display would allow the presentation of tire specific information to the driver; i.e., tell which tire is underinflated. It is possible that drivers will be more likely to remedy a low tire pressure situation if they know exactly which tire is low, since the effort required to examine one tire is obviously less than the effort required to examine all four to determine which one(s) are low and then add air. In other words, providing information as to which tire is low minimizes the amount of effort required by the driver to remedy the underinflation situation, and thus may encourage the corrective action. This display should be considered for incorporation into the standard and presented as an alternative to the use of a telltale (icon) for communicating the condition of tire underinflation. This type of display could be permitted as an alternative to, or in lieu of, a telltale. Of course, a WSB system cannot detect which tire is low, only that one or more tires are low. Therefore, indirect systems would be limited to the use of a telltale.

Figure 8.2 – Vehicle Display for Provision of Warnings for Individual Tires.

If use of a top-view vehicle line drawing display is permitted, some caveats should be set forth. Recognition of the image as a vehicle can vary greatly depending on the features of the drawing. The particular representation tested received 81 percent comprehension. However, other vehicle displays were encountered in the existing systems examination that were found to be difficult to recognize and difficult to determine which way the vehicle was facing (as illustrated in Figure 7.9). It is suggested that consideration of using the exact vehicle line drawing given in Figure 8.2 be considered and comments requested.

In addition, it is suggested that that displays containing a vehicle top-view drawing follow the ISO standard (ISO 2575, 2000) for implementation of this type of display, i.e.:

> "4.4 …If a symbol shows a vehicle or parts of a vehicle in a top, plan view, a vehicle moving from bottom to top on the symbol shall be assumed."

8.8 <u>Recommendations for Presentation of Low Tire Pressure Warnings</u>

There is sufficient data to suggest that the VRTC-developed "Wheel 2-Flat 1" icon should be considered. Comments should be requested on the VRTC-developed "Wheel 2-Flat 1" icon in addition to ISO icon K.11, despite the experimentally determined, extremely low comprehension rate of ISO icon K.11. Comments should also be requested on the alternative vehicle display to assess receptiveness towards offering this type of display as an alternative to use of a telltale for warning of low tire pressure. Based on these comments, a preferred method of providing drivers with low tire pressure warnings can be selected.

9.0 DISCUSSION

9.1 WSB Systems

The WSB Systems failed to alert for the following conditions: two tires on the same side of the vehicle, two tires on the same axle, or all four tires equally low. This limit in sensing capability can be attributed to the general formula for calculating tire underinflation documented in Equation 9.1

$$\left|\frac{(LF + RR) - (RF + LR)}{\text{Average Speed}}\right| \leq \text{Threshold} \rightarrow \text{No warning}, \; > \text{Threshold} \rightarrow \text{TPMS warning}$$

Equation 9.1 – General Formula for WSB System Wheel Radii Calculations

Six possible scenarios for underinflation sensing are listed in Table 9.1. It should be noted that many other scenarios are possible in which multiple tires are low but at different pressures. Ratios were calculated based on example wheel speeds and Equation 9.1.

Table 9.1 – WSB Capability Table – Based on Equation 9.1

Scenario	Ratio (rpm/mph)	Result
One Tire Low	$\frac{(860+863)-(860+860)}{65}=0.05$	TPMS Warning
Two Tires Low, Same Side	$\frac{(860+863)-(863+860)}{65}=0.00$	No Warning Possible
Two Tires Low, Same Axle	$\frac{(863+860)-(863+860)}{65}=0.00$	No Warning Possible
Two Tires Low, Diagonal	$\frac{(860+860)-(863+863)}{65}=-0.09$	TPMS Warning
Three Tires Low	$\frac{(863+863)-(863+860)}{65}=0.05$	TPMS Warning
Four Tires Low	$\frac{(863+863)-(863+863)}{65}=0.00$	No Warning Possible

*For this example a threshold of 0.03 is assumed

Therefore, for three of the six scenarios tested, it was theoretically impossible for the WSB Systems using Equation 9.1 to sense underinflated tires. The results in Table 6.1 agree with the theoretical results in Table 9.1. In other words, none of the systems detected underinflated tires in any of the situations listed as "No Warning Possible" in Table 9.1. Therefore, it is thought that the four WSB systems tested at the VRTC all use sensing algorithms similar to Equation 9.1. However, different sensing algorithms might be developed or additional technology added to the WSB systems that allow sensing of the three scenarios that current systems fail to warn for.

In general, the results from the WSB system show that their ability to sense low tire pressure is dependent on vehicle loading. In all cases but one, the vehicles that warned of significant underinflation warned sooner (with less pressure loss) when the vehicles were at their gross vehicle weight rating as when lightly loaded. This can be attributed to the fact that the rolling radius of modern, standard- profile radial tires will only change about 1mm when the tire pressure drops from 2.1 to 1.4 bars (30 to 20 psi) (See Figure 9.1).

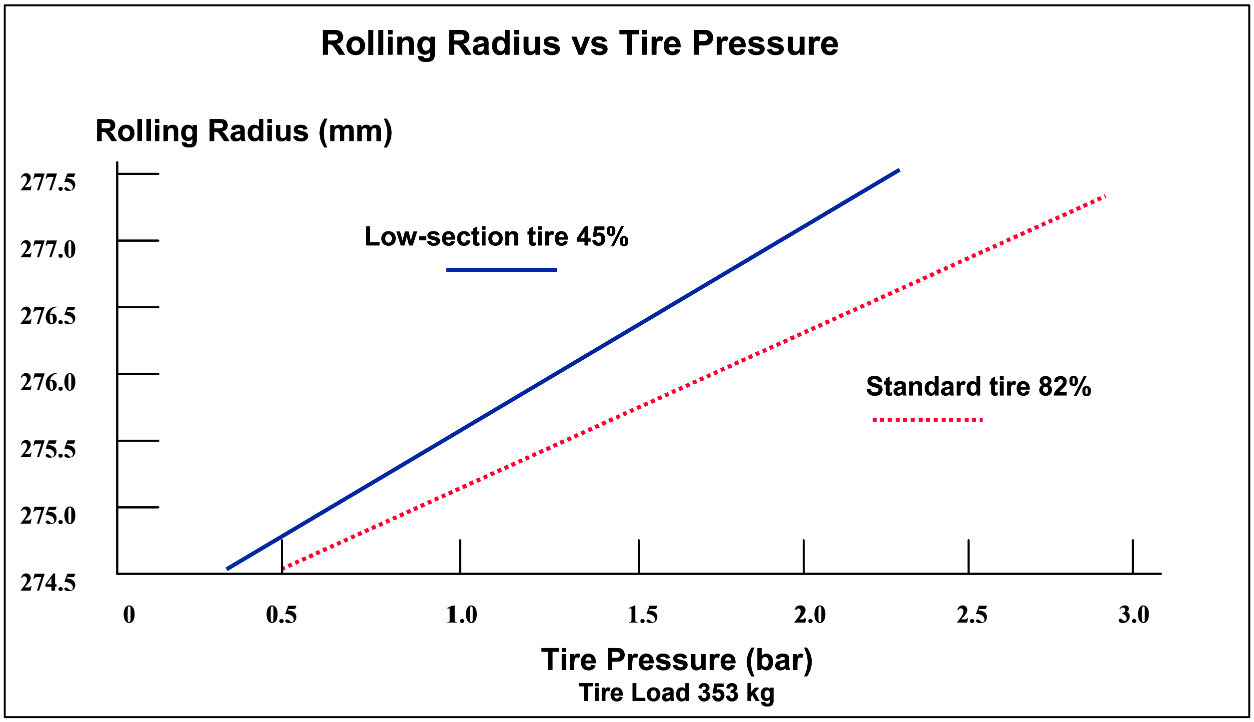


Figure 9.1 – Rolling Radius verses Tire Pressure (graph supplied by BMW AG, 2001)

For the "standard" tires referred to in Figure 9.1, a 33 percent drop in tire pressure from 2.1 to 1.4 bars (30 psi to 20 psi) represents less than the 1 mm (0.4 %) change in rolling radius overall. The wheel-speed based systems must be sensitive enough to detect a millimeter (0.040 inch) or less change in the rolling radius of the tire to warn within 30 percent of placard pressure. The sensitivity of operational factors on tire circumference, which is directly related to tire radius, is detailed in Table 9.2.

While tire pressure changes tire rolling circumference at about 0.03 percent per 1 psi, tire load changes the rolling circumference by 0.08 percent per 100 lb of tire load.[3] In a typical vehicle, if the tire pressure changes 10 psi, the tire circumference changes 0.26 percent. If a typical vehicle's load changes 700 lb (175 lb per tire) between LLVW and GVWR, the tire circumference changes 0.14

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[3] Represents general trends on the influence of operating factors on tire rolling circumference observed by BMW AG. Data was presented in an information session between BWM AG and NHTSA.

percent; which has half as much influence on tire circumference as the 10 psi change in pressure. This explains for the significant changes in warning activation pressure thresholds with vehicle loading. However, as documented earlier, the activation threshold of a WSB system was highly repeatable for a given load.

Table 9.2 – Influence of Operational Factors on Tire Rolling Circumference

(table supplied by BMW AG, 2001)

Factors	**Influence on Tire Rolling Circumference**
Tire Pressure	Δ 0.38 % / 1 bar (14.5 psi)
Load	Δ 0.17 % / 100 kg (220 lb)
Speed	Δ 0.05 % / 10 km/h (6.2 mph)
Acceleration	Δ 0.22 % / 0.1 g
Track	Δ 0.13 % / 1 degree
Camber	No influence
Tire Wear	Δ 0.19 % / 6.0 mm (0.236 in)
Production Tolerance	Δ 0.07 %

9.2 Temperature Compensation

A major issue encountered when designing tire pressure monitoring systems is determining when to warn for underinflation. Monitoring systems that give false warnings or overly frequent warnings can quickly erode consumer confidence and lead to unnecessary repair trips to the dealer. Systems that do not warn quickly enough can allow tire damage to occur while in the underinflated condition. The most significant challenge encountered when setting a warning threshold is the fact that the tires heat up and increase their contained air pressure during operation. Based on the Ideal Gas Law, the contained air of a tire will rise 0.5 to 1.0 psi per 10°F increase in tire air temperature. During typical operation, VRTC's measurements show a typical passenger vehicle tire will rise 2 to 5 psi during normal operation. Since tires are excellent thermal insulators, the tire air will in general reach a steady state operating temperature regardless of ambient conditions. The implication of this is that tire air temperature and pressure will rise more on a cold winter day than on a hot summer day. An illustration of this can be seen in Figure 9.2.

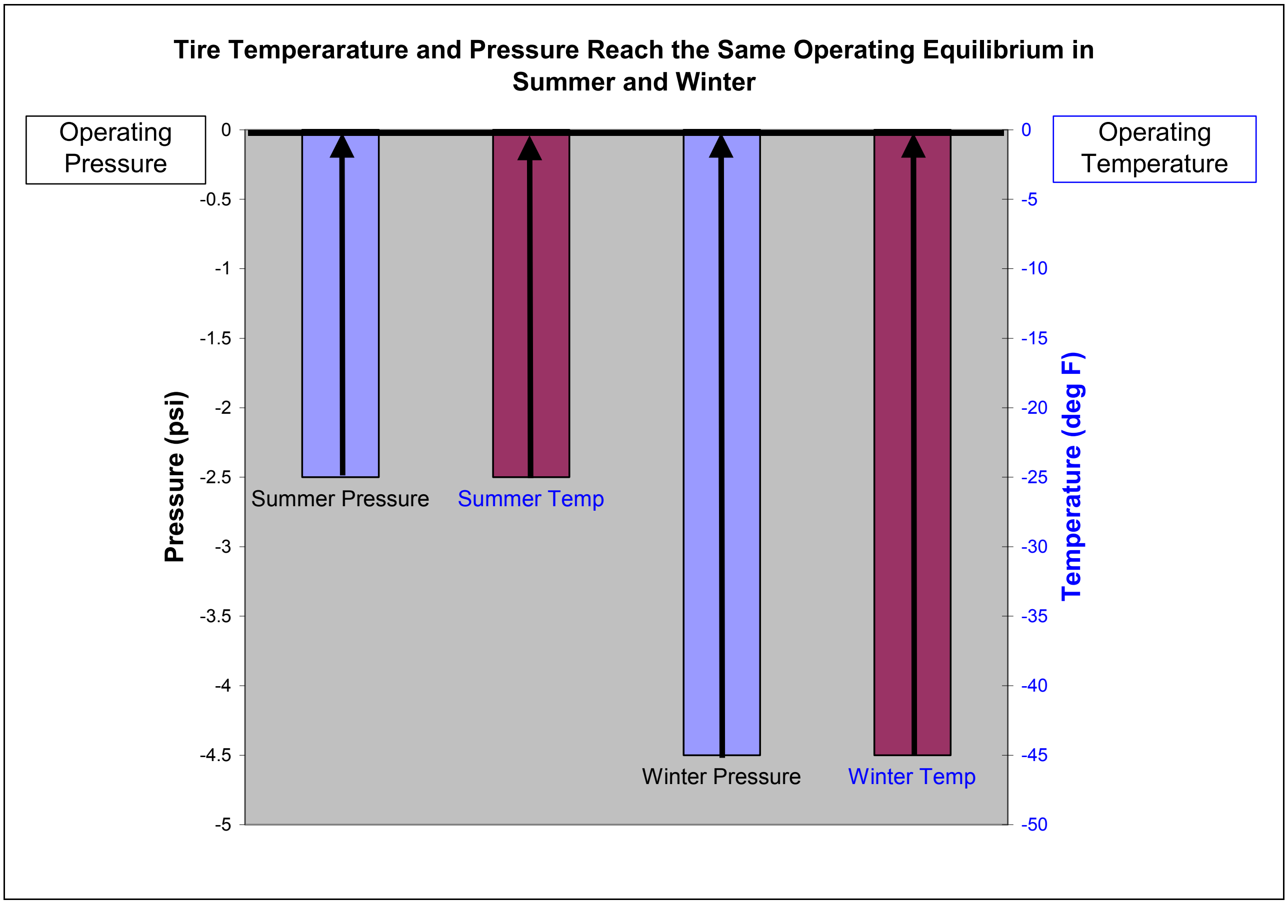

Figure 9.2 – Rise in Tire Pressure and Temperature During Different Ambient Conditions

Another implication of thermal insulation properties of tires is that they take about an hour to cool down to ambient conditions from steady-state temperatures. For example, Figure 9.3 documents the rise in internal tire pressure and contained air temperature for an underinflated tire on a minivan that is doing brake snubs (60 to 20 mph brake applications at 10 ft/s^2 deceleration during each mile of driving). After 20 minutes of driving the vehicle was stopped and the tires allowed to cool in 32°F ambient temperature. Only after 70 plus minutes of cooling does the tire pressure return to the original cold placard pressure.

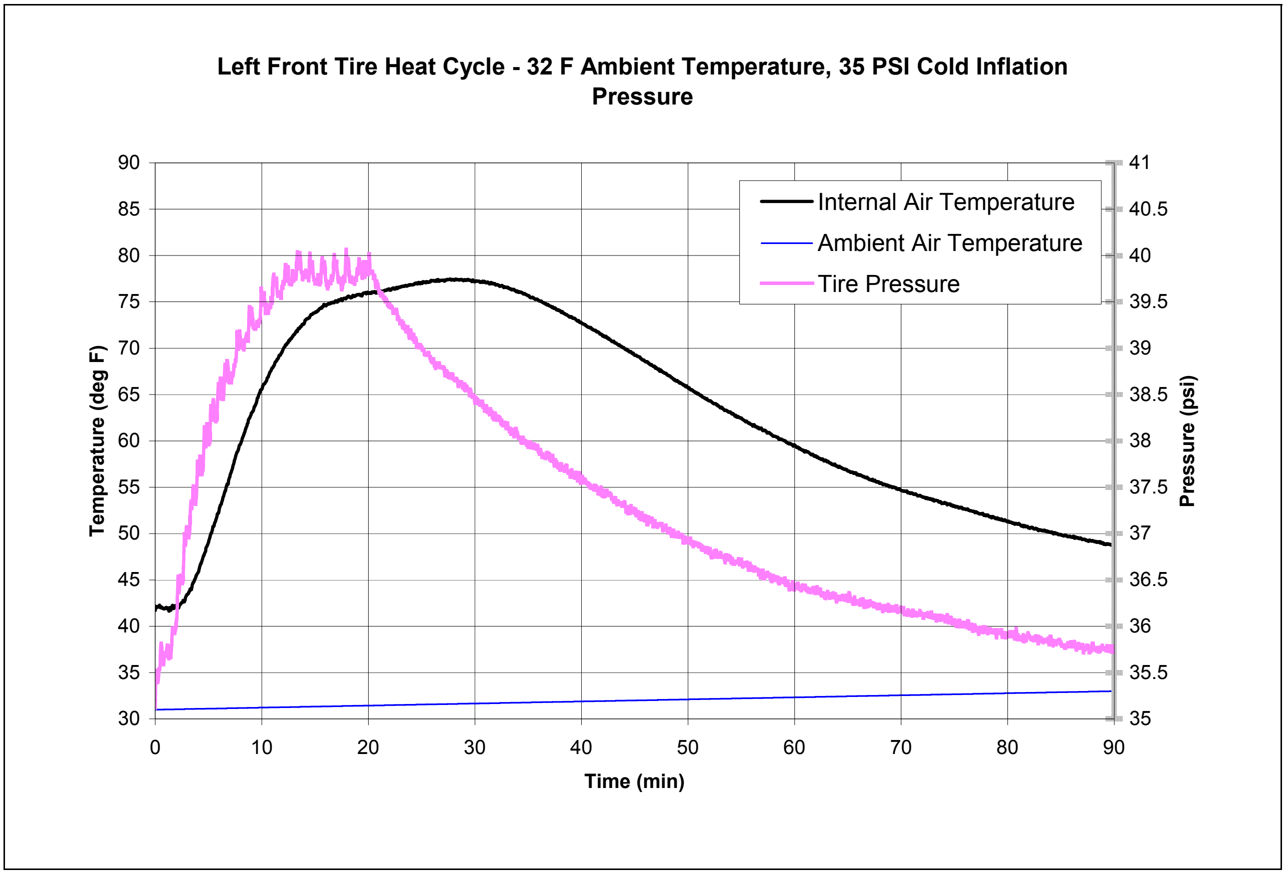

Figure 9.3 – Left Front Tire of Minivan during Brake Snubs with Underinflation

Therefore, consumers that check their tire pressure at service stations after the tires have risen to operating temperature (15+ minutes of continual driving) will be measuring the elevated warm pressure. A tire that is significantly underinflated while cold (20 % below placard pressure) may appear close to proper inflation if checked, for example, while still warm at a service station[4].

Several scenarios involving different underinflation ranges for a bi-level TPMS (underinflation advisory and warning) are shown in Figure 9.4. Scenario 1 documents the normal operating range of a tire properly inflated to placard cold inflation pressure.

[4] http://www.rma.org/tiresafety/tiresafetybrochure.pdf

Figure 9.4 – Underinflation Scenarios

For Scenario 1, the tires are set to the placard cold inflation pressure of 30 psi in daylight hours. Though the tire manufacturers state that tire pressure should be set during the coldest part of the day, setting the pressure during daylight hours is probably more typical. The increase in tire pressure from operation and the decrease in tire pressure when the ambient temperature drops can produce significant tire pressure fluctuations. Since Scenario 1 represents proper inflation of the tires, there should be a sufficient margin between the lowest pressure of the day and the first threshold (underinflation advisory) to prevent false alarms. This margin should also accommodate the error of the tire pressure monitoring system and the consumer’s tire gauge.

In Scenario 2, the cold inflation pressure is below placard but initially above the underinflation advisory level. Temperature fluctuations can cause the cold inflation pressure to occasionally drop below the underinflation advisory threshold. Once the low pressure is detected, the system should advise and continue to advise regardless of tire heating. The reason for this is that tires specified for a 30 psi cold inflation pressure should be operating in the 30 to 35 psi range, not the 25 to 30 psi range. Either the tire has lost enough air, or the ambient temperatures have dropped enough that an underinflation advisory is warranted. If the underinflation advisory threshold is fixed at 20 % low, the vehicle may operate for a period of time with tire pressures down to 24 psi before the advisory activates.

To expedite detection of a tire underinflation, some systems have adopted temperature compensated advisory thresholds. These systems calculate what the placard cold inflation pressure should be at the current tire air temperature, and then compare the current tire pressure to that number. If the current inflation pressure deviates more than a set amount from the "temperature-compensated cold inflation pressure", the advisory activates (even if the tire pressure well above the normal advisory threshold). Figure 9.5 displays the increase in size of the possible advisory range with temperature compensation.

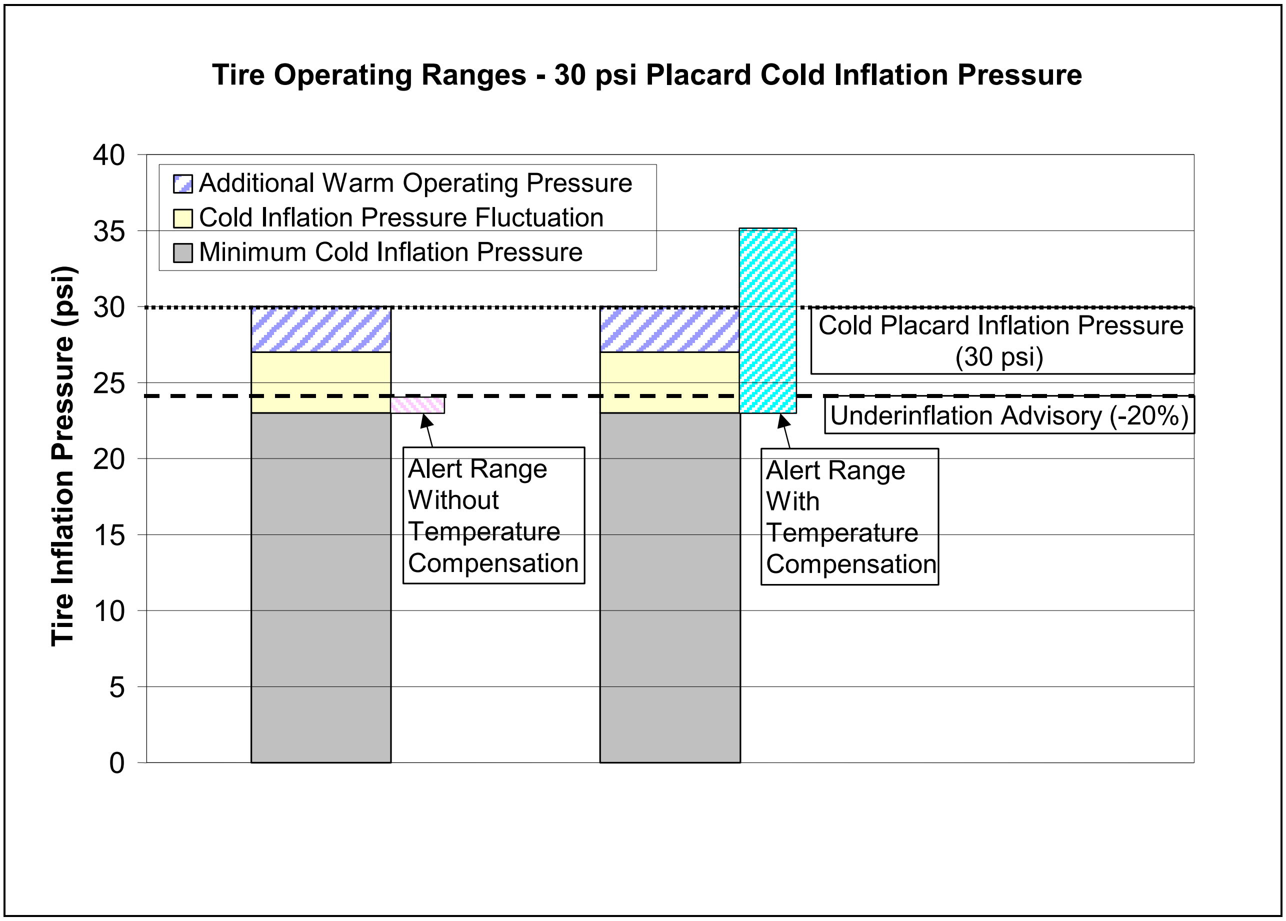

Figure 9.5 – Increase in Advisory Range for Scenario #2 with Temperature Compensation

Again, even if the tires are well above a typical underinflation advisory threshold while warm, if the operating pressure is a certain percentage below what it should be at that tire air temperature, the pressure underinflation advisory will sound.

The main problem with temperature compensation comes from the fact that the "cold" inflation pressure is not officially referenced to a specific ambient temperature level. The RMA, TRA, and

ETRTO define "cold" as the prevailing ambient temperature[5]. What exactly is the prevailing ambient temperature and the time of day at which it occurs is not specified. Unless the system registers the current ambient temperature at startup, it is difficult to have a reference temperature for the cold inflation pressure. The two systems with temperature compensation, System E and J, have taken different approaches to this problem.

According to System J's owner's manual, the system references the cold inflation pressure to room temperature (18°C, 64.4°F). System J's receiver displays not only current tire pressure and temperature, but also the deviation of current pressure from the temperature adjusted cold inflation pressure value. The first warning was a "Pressure Deviation Alert" that activated when the deviation of the current pressure from the adjusted cold inflation pressure exceeds a set amount. The user can set this deviation tolerance between 2 and 20 psi. If the contained tire air temperature is more than 10°F above 65°F, and the pressure is at or below the calculated temperature-compensated cold inflation pressure, the receiver displays "-x psi" (inferring that the tire pressure is low by x psi for that temperature). For approximately each 10°F increment in tire air temperature above 65°F, the display will list add 1 psi to the "-x psi" amount. The same process happens for 10°F increments below 65°F, with the display instead showing "+x psi" deviations (inferring that the tire is overinflated at this temperature).[6]

Fixing the cold inflation pressure at a set temperature is problematic. The National Climatic Data Center lists the average annual ambient temperature for the United States from 1990 to 2000 as 53.57° F (12°C) [11]. This is 10.83° F (6°) lower than System J's 64.4°F (18°C) reference point (though most vehicles are operated during daytime when it is warmer). For people who operate in very warm or cold climates year around, the system might always show a deviation from cold

[5] TRA defines the cold inflation pressures used in their load rating tables as: "The inflation pressures are those taken with the tires at the prevailing atmospheric temperatures and do not include any inflation pressure build-up due to vehicle operation."

[6] Information based on SmarTire Systems Inc., Multi Function Display User's Manual PN 700.0001 GEN II Draft. Results from the evaluation of the system were consistent with the user manual's description.

inflation pressure if the reference temperature is fixed at 18°C (64.4°F). That is why System J allows the temperature compensation feature to be disabled entirely.

System E had a different approach. When the user sets the tire pressures and initializes the system, the pressure is referenced to the current tire air temperature, which is equal to the current ambient temperature as well. If the system senses the tire temperature being more than 36°F (20°C) below the initialization temperature for more than two weeks, the system sets off a warning and must be reinitialized. The user is advised to recheck tire pressures (cold) and must reset the system at the new temperature.

In Scenario 3 of Figure 9.4, the system must detect the low cold inflation pressure before the tires warm up and their pressures rise above the threshold. Both a fixed or temperature compensated advisory would activate in this pressure range. However, it may take an appreciable amount of time before the second notification of underinflation, the underinflation warning, is activated.

Clearly in Scenario 4, the system's underinflation warning should activate. This warning threshold should be fixed, since a temperature compensated threshold may allow very low tire pressures in extreme cold environments.

Temperature compensated warnings may help eliminate nuisance warnings due to daily temperature fluctuations while giving the vehicle operator more useful tire information. Conversely, the algorithm for temperature compensated warnings is very complicated and requires that the cold inflation pressure be referenced to a temperature level. As previously mentioned, many vehicles currently on the market monitor ambient temperature as a driver convenience. The pressure-sensor based TPMS could reference the cold placard inflation pressure to the coldest temperature observed that day and compensate the advisory accordingly.

Overall, temperature compensation can provide important benefits. The underinflation advisory is most likely to be activated shortly after the vehicle begins moving (tires cold). It is assumed that most drivers will eventually travel to a service station to service the low tire(s). If the vehicle is driven a sufficient distance to heat the tires before arriving at the service station, the tires will have an elevated pressure. Taking Scenario 2 from Figure 9.4, the 30 psi tire at 24 psi cold can be at 27 psi (or higher) by the time the vehicle reaches the service station. Instead of adding necessary 6 psi, the operator only adds 3 psi to raise 27 psi to 30 psi (assuming their tire gauge is accurate). If the driver were to check a "Pressure Deviation Display", it would tell them to add the proper 6 psi since the cold inflation pressure would have normally risen to 33 psi at this higher tire air temperature.

9.3 Resetting the TPMS After Tire Rotation or Replacement

Tire pressure monitoring systems must be able to accommodate maintenance related changes in inflation pressure, tire rotations, and tire replacement during the vehicle's operating life. All systems evaluated at the VRTC had an interface that allowed the user to inform the TPMS that the tire pressure or location had been changed. Table 9.3 documents the recommended frequency of tire rotations and tire inflation pressure checks.

Table 9.3 – Tire Rotation and Tire Inflation Check Recommendations

Source	**Rotate Tires**	**Check Tire Inflation**
BF Goodrich	6000 to 8000 miles	-
Bridgestone / Firestone	5000 miles	1 month
Dunlop	6000 miles	1 week
GM	6000 to 7500 miles	1 month
Goodyear	6000 miles (car) / 4000 miles (light truck)	2 weeks
Pirelli	6000 miles	2 weeks
Rubber Manufacturer's Association (RMA)	6000 miles	1 month
Average	6000 miles	3 weeks

Note: All figures obtained from the various companies' websites.

Based on the recommendations in Table 9.3, an average distance of 6000 miles between tire rotations and 3 weeks (600 miles) between inflation pressure checks was assumed. Though tire replacement would have the same effect as tire rotation in requiring the WSB systems to be reset, not all PSB systems would need to be reset during the tire replacement if the wheel sensors were returned to the same locations. The average life of a light vehicle radial tire was estimated to be about 45,000 miles and was substituted for a tire rotation at each 45,000 mile increment. These estimates, coupled with NHTSA's average vehicle life estimates, give the frequency of tire rotation and tire replacement. The complete breakdown is contained in Appendix 8 and the results are summarized in Table 9.4.

Table 9.4 – Estimates for the Frequency of TPMS Reset / Retrain

Vehicle Type	**Average Vehicle Lifespan (years)**	**Average Vehicle Mileage in Lifetime (miles)**	**Average Frequency of Rotation (years)**	**Number of Tire Replacements in Lifetime**	**TPMS Resets**
Passenger Cars	12.5	126,678	0.6	2 to 3	19*
Light Trucks	15.5	153,319	0.6	3	23*

*Figure could be less for pressure-sensor based systems since they may not need to be retrained after tire replacement if the wheels are returned to the original locations.

On average, it is estimated that every 7.2 months a driver will have to reset the wheel-speed based TPMS or retrain the sensor locations for pressure-sensor based TPMS due to tire rotation or replacement. This may require up to 23 resets / retrains over the lifetime of a typical light truck. In addition, the owner's manuals of the four WSB and one PSB (System E) also instruct the owner to reset the TPMS after inflation pressure has been manually adjusted. In theory if vehicle owners checked their inflation pressure every 3 weeks (as recommended) and the tires required air 50 percent of the time, this could add another 100 resets over the life of the vehicle. Therefore, the reset /retrain process for both the wheel-speed based and pressure-sensor based TPMS should be simple and straightforward. The condensed TPMS reset / retrain procedures for the ten systems evaluated are listed in Table 9.5.

Table 9.5 – Reset / Retrain Procedures for the TPMS Evaluated

System	TPMS Reset / Retraining Method (From Vehicle Owner's Manuals)
A	▪ Turn key to position 2 ▪ Press system button until the yellow indicator lamp on the instrument panel lights up ▪ Drive for a few minutes
B	▪ Turn ignition to run ▪ Press gage info button on DIC (Driver Information Center) until "TIRE PRESSURE" appears on display ▪ Press and hold DIC RESET button for about five seconds…"TIRE PRESSURE NORMAL" will appear in display ▪ Drive 45 to 90 minutes
C	▪ Turn ignition to ON ▪ Push reset switch until pressure warning light blinks three times ▪ Drive at speeds over 19 mph for 8 hours
D	▪ Turn ignition to position 2 ▪ Press system button until "Set tyre pressure" is displayed ▪ Drive at least 10 minutes
E	▪ Turn ignition to position 2 ▪ Press system button until : "SET TYRE PRESSURE" is displayed ▪ Drive for several minutes for automatic sensor location recognition
F	NA – Prototype
G	Sensors have wheel locations marked on them ▪ Unscrew sensors from valve stems and reattach them to designated tire valve ▪ Press "RESET" on the receiver
H	Only a qualified technician is authorized to retrain the sensor locations
I	▪ Ignition on ▪ Push "Tire" and "Mode" at the same time for ten seconds of more ▪ Push "Tire" to display Fr__Id ▪ Depress front right valve core for 10 seconds until display beeps and flashes ▪ Push "Tire" to display Fr__Id ▪ Continue pressure dropping process for front right, rear right, and left rear tires in that order ▪ Confirm registration by manually deflating each tire and looking for a warning
J	Wheels are externally color coded to indicate the sensor within (color indicates numerically designation) ▪ Press "MODE" to enter tire rotation mode ▪ Press "TIRE" to scroll through locations and "Mode" to select a location for editing ▪ Adjust tire locations to proper sensor numeric, i.e. change right front from "1" (green wheel) to "3" (blue wheel)… ▪ Press "SET" when finished with all four locations

As Table 9.5 documents, resetting the four wheel-speed based systems involves pushing buttons on the dash or in the driver information consoles and then driving the vehicle to allow the system to "relearn" the tire profiles. Resetting the OE pressure-sensor based system with automatic wheel location recognition (System E) was similar, simply push a button and drive the vehicle. System G's sensors have their locations marked on them and just screw onto the valve stems. System H specifies that only qualified technicians should retrain sensor locations. System I's procedures were essentially the same as the installation procedures, requiring a lengthy process of training the sensor locations to the receiver by leaking down each tire in a predetermined sequence. Having gone through this process installing Systems H, I, and J, we think it doubtful that consumers will want to do this 19 to 23 times over the life of their vehicles. System J's "Tire Rotation Mode" was a compromise between automatic location recognition and manual retraining. System J's receiver had a menu that allow the wheel locations to be reassigned, without requiring the tires to be dropped in pressure. This mode did require the user to know what sensor had moved to what location.

10.0 SUMMARY

Research was conducted to examine both commercially available and prototype tire pressure monitoring systems (TPMS). TPMS features examined included the type of warnings given, the thresholds at which they occurred, the time delay from a low pressure occurrence to driver notification, and some of the human factors of the warning information displays. The findings were grouped according to the two system types: Wheel-Speed Based (WSB) and Pressure-Sensor Based (PSB) measurement.

10.1 Hardware Performance Results

A summary of the findings regarding the performance of WSB and PSB TPMS is provided in Table 10.1.

Table 10.1 – Summary of Findings by System Type

Issue	**WSB**	**PSB**
Average Pressure Drop Required to Activate Warning	16 to 32 % underinflation	Average Pressure drop required for underinflation advisory was 27 %, 42 % for significant underinflation warning
Ability to detect underinflated tires	1, 2 (diagonally only), or 3; capability to detect tires at three or four different pressures simultaneously unknown.	Any combination of 1 or more
Warning Threshold Variance	Warning threshold varies with load ▪ Inconsistent from tire to tire ▪ Threshold not easily changed by the manufacturer	Warning threshold range of 10 to 24psi, 20 to 68 % underinflation ▪ Consistent from tire to tire ▪ Threshold easily changed by the manufacturer
Time to Warn	"Time to warn" range of 60 to 630 seconds; very dependent on course (curves are crucial)	"Time to warn" range of 10 to 140 seconds; not very dependent on course
Effects of Tire Heating	Maintains warning despite tire heating	Only some maintain warning when tires heat
Calibration / Training	Calibration difficult, no indicator	▪ Original Equipment Systems: Some may require retraining of sensor locations after tire rotation. ▪ Aftermarket systems: Require retraining of sensor locations after tire rotation; initial training is difficult for some systems; though all will warn of improper training
Battery Life	n/a	5 to 10 years
Durability	Damage unlikely since sensors are shielded	Susceptible to damage or theft for systems with sensors located outside the tire
Tread Depth Sensitivity	Sensitive to tread depth variation	Not sensitive to tread depth variations
Vehicle Loading Sensitivity	Warning activation thresholds highly sensitive to vehicle loading	Not sensitive to vehicle loading
Driving Course Layout Sensitivity	Some systems require left and right-hand turning to properly calibrate and sense underinflation.	Not sensitive to driving course layout
Reset Concerns	Can be reset to use underinflated tires as the baseline for properly inflated tires	Warning levels will be preset by manufacturer; warning status cannot be reset while the tire is underinflated

10.2 <u>Human Factors Examination of Warning Displays</u>

An examination of driver interfaces for existing TPMS showed significant variation in methods of visual warning presentation for both original equipment and aftermarket systems. Most of the visual displays were either difficult to see or hard to comprehend, or both. Auditory warnings were overall fairly similar for all systems. The variation in visual warning presentation demonstrated the need for standardization of the visual warnings of tire underinflation to avoid driver confusion.

A summary of findings from the examination of existing systems and icon development and comprehension testing are listed in the following Table 10.2.

Table 10.2 – Summary of Low Tire Pressure Warning Display Findings

Issue	Findings
Consistency/ Standardization	▪ Methods of providing visual warnings varied greatly from system to system ▪ Need a standard icon and/or vehicle-based wheel-by-wheel display ▪ Most visual displays were difficult to comprehend ▪ An icon was developed which proved to be more recognizable than the ISO icons for indication of low tire pressure ▪ Use of a vehicle-based wheel-by-wheel display, properly oriented, may be a suitable substitute for use of a standard icon.
Conspicuity	Most visual displays were difficult to see (e.g., due to glare)
Method of Warning Presentation	Significant underinflation warning may include visual and auditory signals; underinflation advisory may be only visual.

10.3 Low Tire Pressure Icon Comprehension Testing

Results of the icon comprehension tests showed that recognition was poor for the ISO tire pressure icons (K.10 and K.11). The ISO tire pressure and tire failure icons received the lowest comprehension scores of the 16 icons tested, 38 percent and 25 percent, for K.10 and K.11 respectively. Percent correct observed for the icons based on tire images ranged from approximately 62 percent to 100 percent (6 of the 12 had 100 percent comprehension). The percentage of correct responses associated with the vehicle image icon was 81 percent. Respondents showed near perfect (95 percent) comprehension results for the ISO engine icon, which was used as a baseline for comparison.

Based on these results, it was suggested that an alternative to the existing ISO icons be considered for use in alerting drivers to the condition of low tire pressure. Considering the best recognized features of the icons tested, a single icon (one of the 6 whose results showed 100 percent comprehension) is suggested as that which is most likely to be recognized by the general population. The suggested icon for use as a visual indicator of significant tire underinflation is pictured in Figure 10.1.

Use of a top-view vehicle display showing individual tires (as shown in Figure 10.1) could also be implemented in vehicles for the presentation of low tire information. Use of this display would allow the presentation of tire specific information to the driver, i.e., tell which tire is underinflated. This type of display could be permitted as an alternative to, or in lieu of, a telltale. Of course a WSB system cannot detect which tire is low, only that one or more tires are low. Therefore, WSB systems would be limited to the use of a telltale.

Figure 10.1 – Suggested icon for indication of significant tire underinflation and alternative vehicle-based display.

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12.0 APPENDICES

Appendix 1. Revised System D Calibration Procedures (VRTC)

Instructions:

Vehicle must be driven for 8 hours or more to calibrate ABS-based tire pressure monitoring system. Driving time is actual road time and does not include breaks.

Driving Instructions:

a. For 1 hour:
   i. Drive on 7 ½ mile oval track (HSTT) at 60 mph

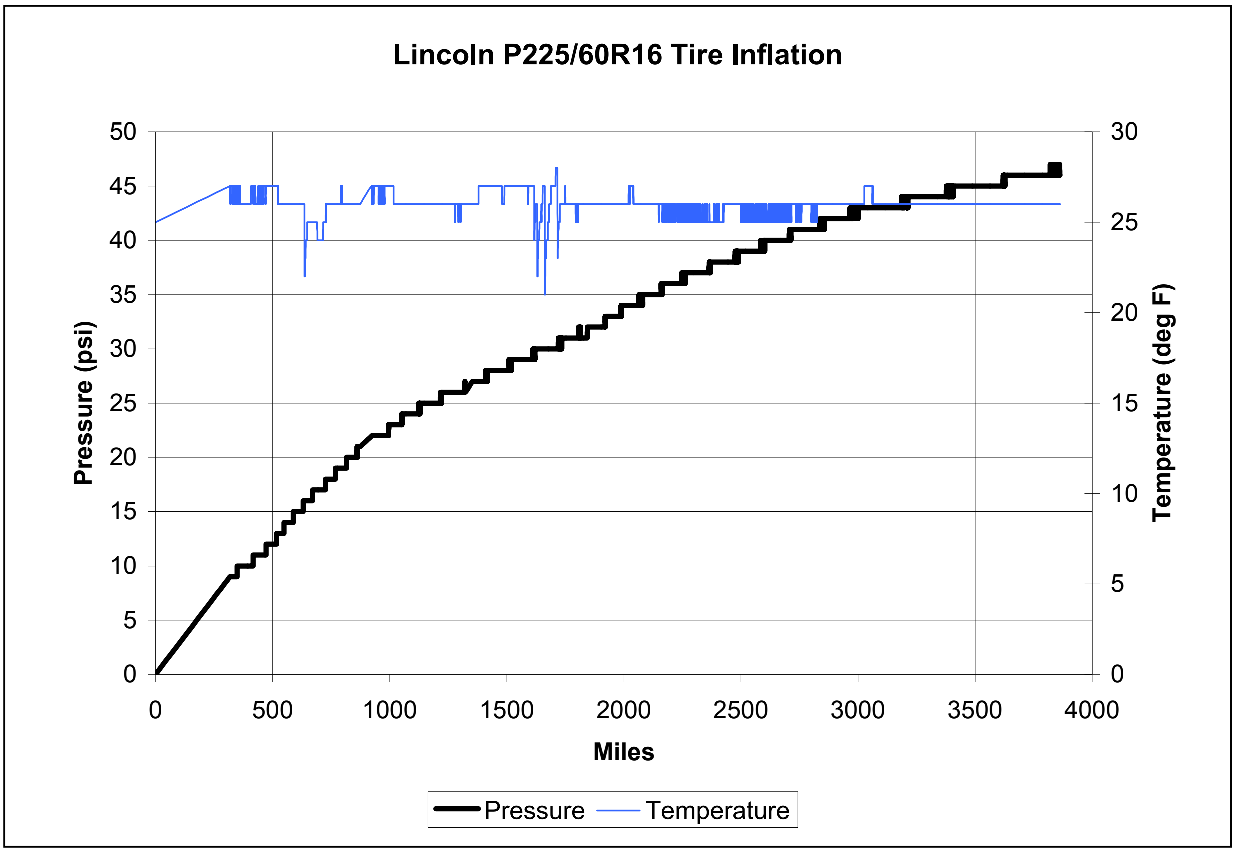
b. Drive for 3 hours:
   i. 10 Figure 8s on the VDA at 35 mph
   ii. 1 clockwise loop on the VDA Winding Course at 22 to 30 mph
   iii. 10 Figure 8s on the VDA at 35 mph
   iv. 1 counterclockwise loop on the VDA Winding Course at 22 to 30 mph

c. Repeat for 3 hours:
   i. 10 Figure 8s on the VDA at 45 mph
   ii. 1 clockwise loop on the VDA Winding Course at 22 to 30 mph
   iii. 10 Figure 8s on the VDA at 45 mph
   iv. 1 counterclockwise loop on the VDA Winding Course at 22 to 30 mph

d. For 1 hours:
   i. Drive on 7 ½ mile oval track (HSTT) at 60 mph

Appendix 2. Cycloid AutoPump Example Tire Inflation Curve

For normally inflated tires, the Cycloid AutoPump's inertial driven compressor adds a maximum of 2 psi per hour of driving. The inflation rate of the pump is high at low pressures and drops off as tire pressure increases. The pump will eventually reach its preset equilibrium level with the tires and will not be able to add more pressure. The inflation system is currently configured to handle cold inflation pressures up to 45 psi; though the pump has the theoretical capacity of 65 psi.



Appendix 3. Tire Pressure Monitoring System Test Procedures

Tire Pressure Monitoring Systems Test Procedures

Pressure-Sensor Based TPMS

1. First Static Test - Accuracy

(This test is intended to test the accuracy and response time of the PSB pressure measurement system. The vehicle is tested indoors at 65 to 70°F. The tires spun for a minimum of 20 minutes to "wakeup" the sensors and give them two sensing cycles prior to the accuracy test. The wheels are spun for 10 minutes at each pressure increment to allow the system to update current tire status at least once.)

a. Vehicle indoors overnight, on lift
b. Check tire pressure and adjust to door placard pressure
c. Place car in drive or place electric motor under tire and let spin at 20 mph for a minimum of 20 minutes prior to testing
   i. start filming TPMS display
   ii. record ambient air temperature
   iii. lower Right Front (**RF**) tire pressure by 2 psi
   iv. spin tire for 10 minutes, confirm that display is functioning properly
   v. continue the process of lowering the tire pressure by 2 psi and spinning for 10 minutes <u>until</u> first underinflation notification activates (there are usually two notifications, underinflation advisory and significant underinflation warning)
   vi. record TPMS activation pressure after the wheel has fully stopped
   vii. lower pressure by 2 psi to the next test pressure and spin for 10 minutes
   viii. continue process <u>until</u> second warning activates or until the minimum pressure of 14 psi is attained
   ix. refill the tire to placard tire pressure
d. Repeat process for **LR** tire

(The following rapid tire deflation test is intended to measure the response time of the first and second warning to a large tire puncture.)

e. Repeat process for **LF**, then **RR** tire, using a rapid deflation valve with a flow rate approximately equal to a valve stem with the valve core removed instead of the manual 2 psi increments used in step c.
   i. record time at start of deflation
   ii. open dump valve and spin tires to 20 mph
   iii. if possible, record elapsed time to underinflation advisory
   iv. if possible, record elapsed time to underinflation warning
f. Record final ambient air temperature
g. Refill tires to placard tire pressure
h. Wait one hour and readjust tire pressure to recommended pressure

i. Record indoor temperature
j. Move vehicle to outdoors and leave overnight

2. Second Static Test - Temperature Effects

(This test is intended to evaluate the effects of temperature changes on PSB system performance. It explorers the influence of temperature compensation on warning thresholds.)

a. With the vehicle still outdoors, record outdoor ambient weather conditions
b. Place vehicle on four jack stands
c. Check, but do not adjust tire pressures from previous day
d. Repeat First Static Test procedures c through g
e. Move vehicles indoors and leave overnight

3. Third Static Test - Accuracy

(This test is a repeat of the first static test and is intended to evaluate the repeatability of the warning thresholds)

a. Repeat First Static Test procedures a through g indoors (again for accuracy)

4. Human Factors Evaluation

(A comprehensive evaluation of each user interface will be completed)

a. The vehicle will remain on the lift from the Third Static Test and run through various deflation cycles to evaluate the following human factors considerations:
   i. warning method
   ii. context of message
   iii. message timing
   iv. failure messages
   v. reset controls

5. Loaded Dynamic Test - Dynamic Warning Thresholds

(This test evaluates the on-road response of the PSB system to a slow leak and also a medium sized tire puncture. In addition, the leaks are stopped as soon as the system's first warning activates. The warning condition is monitored as brake snubs heat the tires and raise pressure back above the warning threshold. If the warning shuts off at the higher warm tire pressure, this may be an indication of possible "nuisance" warnings.)

a. Load vehicle to GVWR on calibrated vehicle scales (do not exceed either axle's GAWR)
b. Move vehicle outdoors and allow tires to cool for at least one hour (test at ambient "cold" inflation pressure)
c. Record ambient weather conditions
d. Adjust all tires to placard cold inflation pressure
e. Test on the High Speed Test Track, Bituminous Asphalt Lane
f. Vehicle speed: 60 mph
g. Start data acquisition at a 20 Hz rate

h. Begin slowly leaking Right Front (**RF**) tire pressure at approximately 0.025psi/sec (1.5 psi/min) - Stop if 14 psi is reached

i. Trip first digital marker when the significant underinflation warning activates and stop the air leak
   - i. get permission from TRC Control Tower to complete brake snubs in asphalt lane
   - ii. drive 3 laps (22.5miles) around TRC test track. Initiate a 60 to 20 mph brake snub at 10 ft/s^2 deceleration during each mile of driving.
   - iii. Record warning signal status (on / off) at end of run.

j. Stop DAQ and refill the tire to placard tire pressure

k. Repeat steps c through j for **LR** tire

l. Initiate a rapid deflation rate of 0.1psi/sec (6psi/min) for **RR** tire - Stop if 14 psi is reached

m. trip first digital marker when underinflation advisory activates (if the system has two levels of notification of underinflation)

n. trip second digital marker when the significant underinflation warning activates

o. stop immediately at a safe track location and refill the tire to placard tire pressure

p. Repeat step l for **LF** tire

q. Record final ambient weather conditions

6. Loaded Dynamic High Speed Test

(Explores the effects of high vehicle speeds on the TPMS threshold. High speeds will heat the tires, raise the pressure inside, and possibly turn off the low tire pressure warning. This is similar to the previous test but high speed is substituted instead of brake snubs for tire heating.)

a. Load vehicle to GVWR on calibrated vehicle scales (do not exceed either axle's GAWR)

b. Record ambient weather conditions

c. Test on the High Speed Test Track, Bituminous Asphalt Lane

d. Start data acquisition at a 5 Hz rate

e. Deflate **LR** tire to 2 psi below the average value of the first low pressure indication from the two indoor static tests.

f. Drive vehicle at 20 mph and confirm that warning system has detected the low tire pressure

g. If warning does not occur, lower tire pressure in 2 psi increments until dynamic activation occurs - Stop if 14 psi is reached

h. Drive the vehicle at 75 mph for 22.5 miles (3 laps around HSTT) and note the status of the TPMS warning

i. Stop data acquisition

j. Record final ambient weather conditions

7. System Failure Effects Test

(Since consumers will tend to rely on this monitoring system as a warning system, the driver must be alerted to sensor failure.)

a. If possible, the TPMS will be made inoperable and the mode by which the system informs the driver will be noted
    i. this will entail coming back to the VRTC and removing or disabling one sensor and then driving on the HSTT until a warning is detected or 0.5 hours is reached.

Wheel-Speed Based TPMS

1. Sensing Capabilities Test

(For the following tests, it is only necessary to test whether the system activates for multiple tires low or not. ABS-based systems function better on roads with curves, hence the Winding Road Course "WRC" is used. This is a "best-case" scenario, with just the empty vehicle and driver for load. The tires start out being set cold at recommended inflation pressure. The test tire(s) is set to 50 percent below the current pressure in that tire after the calibration and warm-up laps are completed. The vehicle is given more than 10 miles of driving to alert that the tire or tires 50 percent underinflated. Often, full resetting the system between tests requires vehicle specific procedures or even full recalibration.)

a. Load vehicle to LLVW on calibrated vehicle scales: LLVW = Empty vehicle + driver + observer + instrumentation [Curb weight + 500 lb
b. Allow tires to cool for at least 1hr
c. Set tire pressure to exact placard recommendations for given load
d. Properly calibrate TPMS
e. At WRC - drive 2 laps (3.0 miles) with all tires properly inflated
f. Set **RF** tire to 50 percent below the current tire pressure or 16 psi minimum (for safety).
    i. record pressures.
    ii. zero the trip odometer
    iii. drive 30mph until warning activates or 7 laps (10.5 miles) have elapsed
    iv. if TPMS warns, stop immediately and record distance to activation
    v. wait 15 minutes in pit area
    vi. after tires have cooled, refill tire to original recorded tire pressure
    vii. reset warning according to procedures (reset, do not recalibrate unless it is required by the reset procedure)
g. Repeat e.& f. for **LR** tire
h. Repeat e.& f. for **RF** and **LF** tires simultaneously
i. Repeat e.& f. for **RF** and **RR** tires simultaneously
j. Repeat e.& f. for **LF** and **RR** tires simultaneously
k. Repeat e.& f. for **RF**, **LF**, **LR** tires simultaneously
l. Repeat e.& f. for **all four** tires simultaneously

2. First Accuracy Test - LLVW

(For the two tires, RF and LR, it can be determined exactly where the system activated, i.e. 20 percent low, 30 percent low... A good indicator of WSB system resolution)

a. Load vehicle to LLVW on calibrated vehicle scales: LLVW = Empty vehicle + driver + observer + instrumentation + ballast. Curb weight +500 lb
    i. Have ABS System fully recalibrated
b. Record ambient weather conditions
c. Vehicle speed: 60 mph
    i. start data acquisition at a 20 Hz rate
    ii. begin slowly leaking Right Front (**RF**) tire pressure at 0.025psi/sec (1.5 psi/min) - 14 psi minimum
    iii. if warning is observed:
        (1) trip first digital marker when significant underinflation warning activates and stop the air leak
        (2) drive 3 laps (22.5 miles) around TRC HSTT. Initiate a 60 to 20 mph brake snub at 10 ft/s^2 deceleration during each mile of driving. Record warning signal status (on / off)
    iv. Stop leaking tire pressure if 14 psi is reached
        (1) if no TPMS warning is observed, drive one lap on the HSTT (7.5 miles) with 14 psi in the test tire
    v. stop DAQ and refill the tire to placard tire pressure
    vi. reset TPMS warning (see owner's manual)
    vii. drive for no less than 10 minutes in the 15 to 40 mph range
    viii. drive for no less than 10 minutes in the 40 to 70 mph range
d. the TPMS light should have extinguished, if not, recheck tire pressure and repeat driving through the two speed ranges
e. Repeat for **LR** tire

3. Second Accuracy Test - LLVW

a. Have ABS System fully recalibrated
b. Repeat First Accuracy Test - LLVW

4. First Accuracy Test - GVWR

a. Load vehicle to GVWR on calibrated vehicle scales (do not exceed either axle's GAWR)
b. Repeat First Accuracy Test procedures at GVWR

5. Second Accuracy Test - GVWR

a. Have ABS System fully recalibrated
b. Repeat First Accuracy Test procedures at GVWR

6. Human Factors Evaluation

a. Repeat PSB TPMS Human Factors Evaluation
b. Disable the ABS and evaluate TPMS response
c. Change tires to different diameter tires but do not manually reset the TPMS as directed in owner's manual. Evaluate TPMS response.

7. **Loaded Dynamic Test on Loose Surface**

   (WSB systems have trouble warning on loose surfaces since they rely on wheel speed measurements. On loose surfaces, the wheels are constantly changing speed due to varying levels of slip and loss of solid contact with the surface.)

   a. Load vehicle to GVWR on calibrated vehicle scales (do not exceed either axle's GAWR)
   b. Repeat First and Second Accuracy Tests on the gravel load
   c. Follow posted gravel road speed limits

8. **Empty Dynamic Test on Loose Surface**

   a. Load vehicle to LLVW on calibrated vehicle scales: LLVW = Empty vehicle + driver + observer + instrumentation + ballast [Curb weight +500 lb
   b. Repeat one-tire Accuracy Tests on the gravel load
   c. Follow posted gravel road speed limits

Notes:

Weather condition data includes: Time, dry bulb temperature in deg F, wind speed and direction, percent relative humidity, barometric pressure in inches of mercury (Hg), and sky and track conditions.

Appendix 4. TPMS Reset Procedures for WSB Systems

Set tires to placard cold inflation pressure. If tires were set properly before going out and are now hot, set low tires to the same nominal pressure that the originally inflated tires have risen to.

System A

Reset

Round the inflation pressure in the tires to the same nominal pressure per axle

Push RDW until red lamp goes out

Drive on WRC

Calibration

Set tires cold to placard pressure

Turn key to position 2

Press RDW button until yellow indicator lamp on instrument cluster lights up

Drive on WRC for 1 hr between 10 to 62 mph, use multiple torque and speed ranges

Drive on HSTT 15 min between 10 to 62 mph

Drive on HSTT 15 min between 62 to 80 mph

System B

Reset & Calibration

Round tires to the same nominal pressure (set cold for initial calibration)

Press GAGE INFO button until TIRE PRESSURE appears

Hold RESET until TIRE PRESSURE NORMAL appears

Drive on HSTT

10 minutes at 15 to 40 mph

10 minutes at 40 to 70 mph

10 minutes at 70 to 90 mph

System C

Round tires to the same nominal pressure (set cold for initial calibration)

Turn off ignition

Turn key to position 2

Press button until the display says “SET TIRE PRESSURE” for several seconds

Drive 15 minutes on the WRC

System D

Reset

Round tires to the same nominal per axle pressure

Drive until light warning light goes out

Calibration

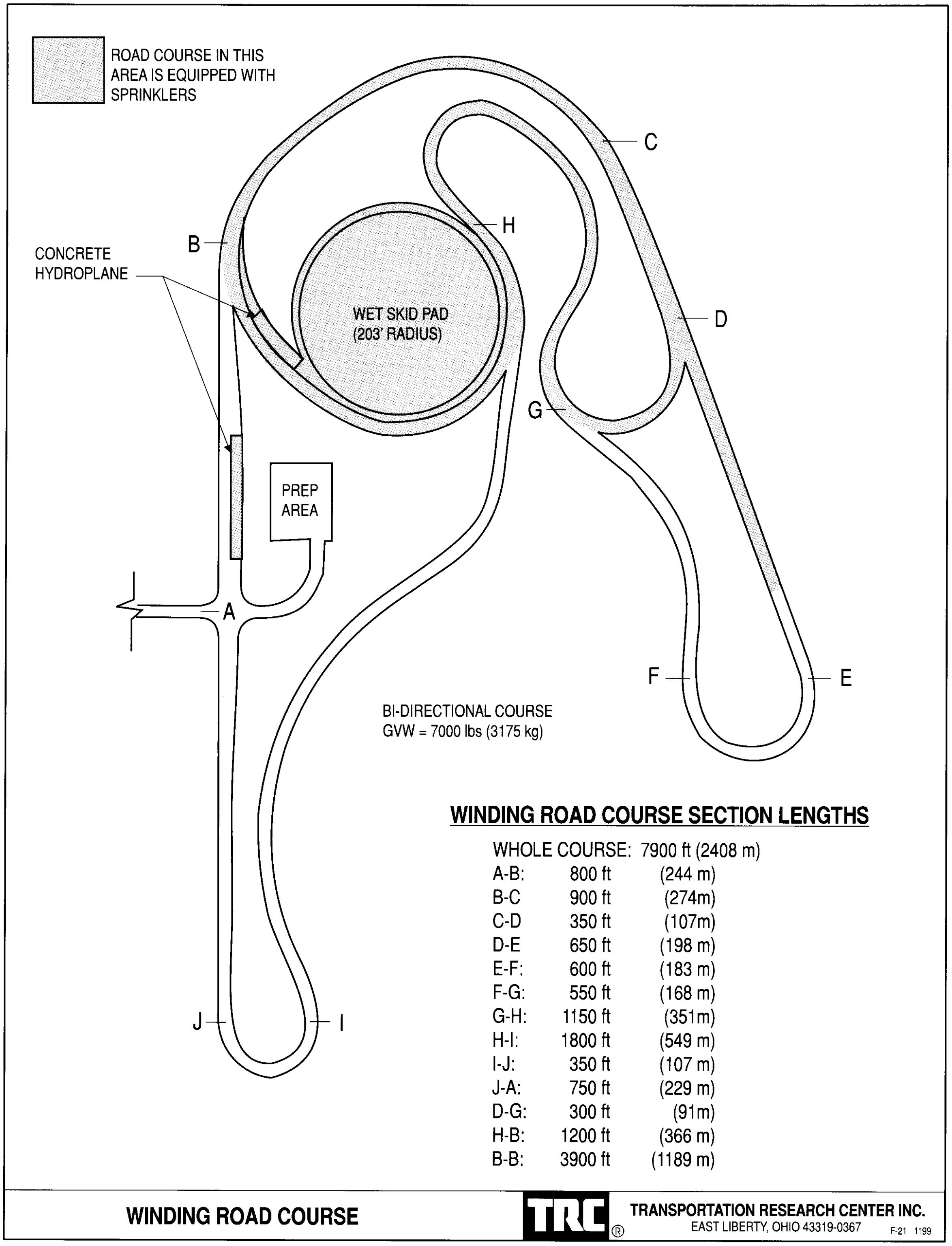
Set tires cold to placard pressure

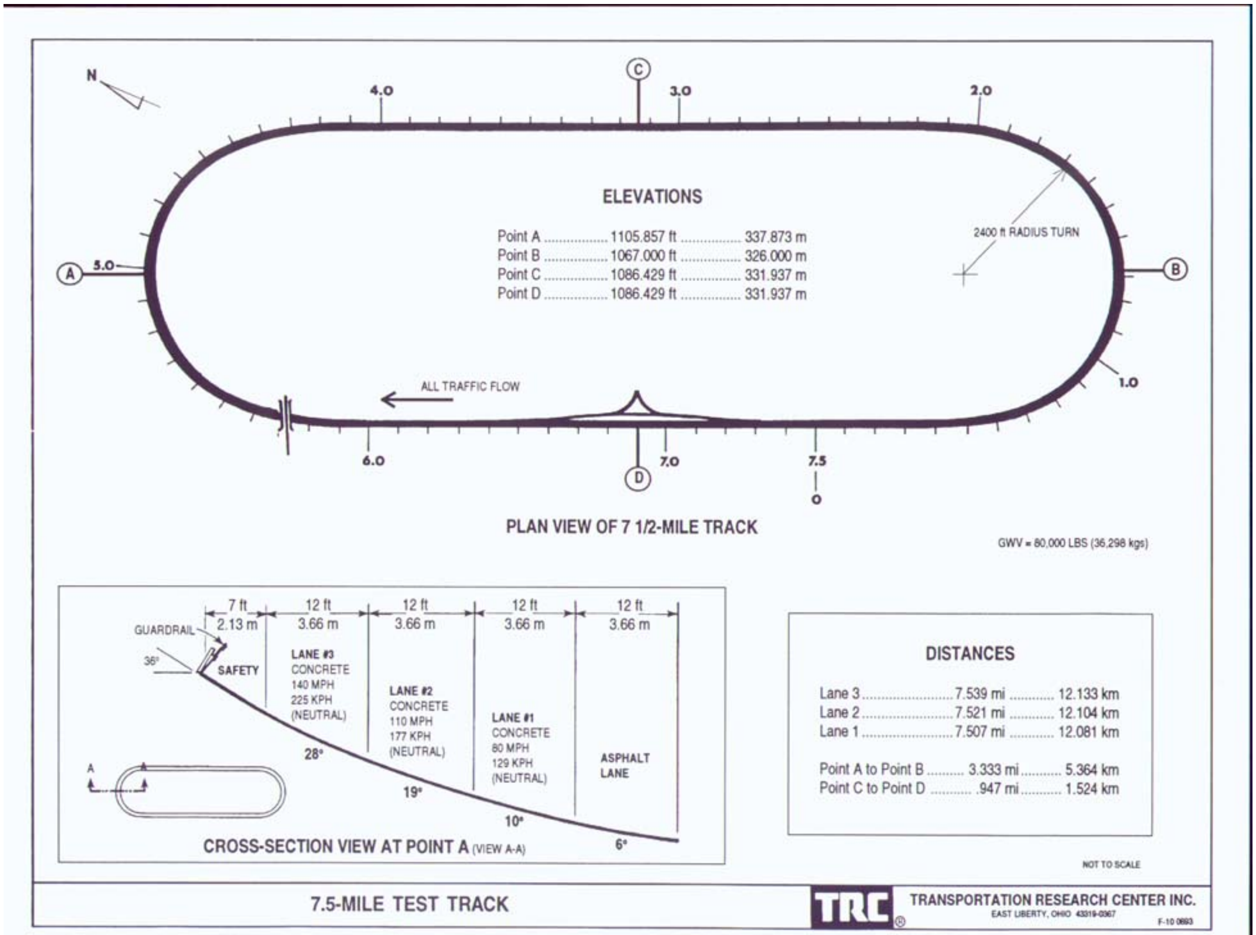
Ignition on

Hold reset button until warning light flashes 3 times

Drive for up to 8 hours depending on maneuvers

Appendix 5. Test Courses





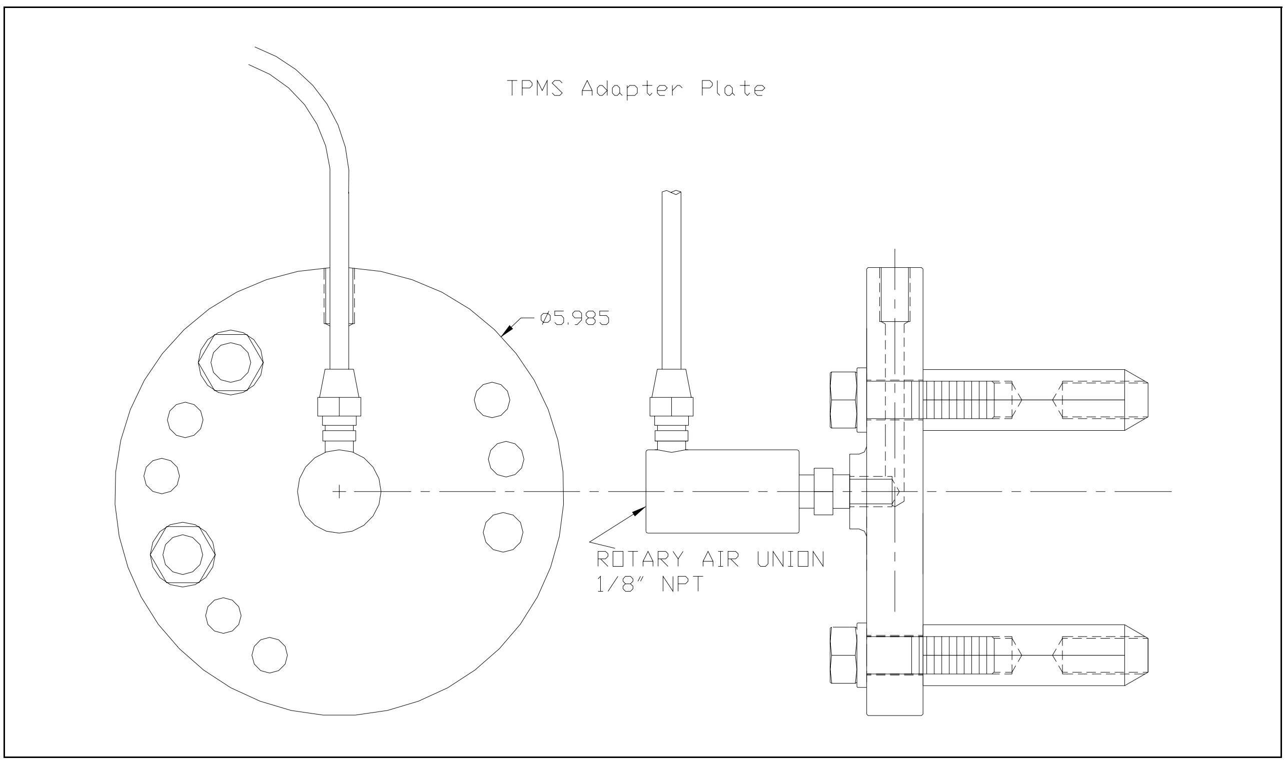
N
4.0
3.0
2.0
5.0
1.0
6.0
7.0
7.5
0
A
B
C
D
ELEVATIONS
Point A .... 1105.857 ft .... 337.873 m
Point B .... 1067.000 ft .... 326.000 m
Point C .... 1086.429 ft .... 331.937 m
Point D .... 1086.429 ft .... 331.937 m
2400 ft RADIUS TURN
ALL TRAFFIC FLOW
PLAN VIEW OF 7 1/2-MILE TRACK
GWV = 80,000 LBS (36,298 kgs)
7 ft 2.13 m
12 ft 3.66 m
12 ft 3.66 m
12 ft 3.66 m
12 ft 3.66 m
GUARDRAIL
36°
SAFETY
LANE #3 CONCRETE 140 MPH 225 KPH (NEUTRAL)
LANE #2 CONCRETE 110 MPH 177 KPH (NEUTRAL)
LANE #1 CONCRETE 80 MPH 129 KPH (NEUTRAL)
ASPHALT LANE
28°
19°
10°
6°
CROSS-SECTION VIEW AT POINT A (VIEW A-A)
DISTANCES
Lane 3 .... 7.539 mi .... 12.133 km
Lane 2 .... 7.521 mi .... 12.104 km
Lane 1 .... 7.507 mi .... 12.081 km
Point A to Point B .... 3.333 mi .... 5.364 km
Point C to Point D .... .947 mi .... 1.524 km
NOT TO SCALE
7.5-MILE TEST TRACK
TRC
TRANSPORTATION RESEARCH CENTER INC.
EAST LIBERTY, OHIO 43319-0367
F-10 0693

Appendix 6. Vehicle Weights at Testing

System	Type	Test Condition	GVWR	GAWR Front	GAWR Rear	FRONT (lb)	% GAWR Front	REAR (lb)	% GAWR Rear	TOTAL (lb)	% GVWR
A	Pass Conv.	LLVW	4630	2183	2579	1875	85.9%	2038	79.0%	3913	84.5%
A	Pass Conv.	GVWR	4630	2183	2579	2156	98.8%	2463	95.5%	4619	99.8%
B	Full Size Sedan	LLVW	4685	2517	2168	2317	92.1%	1618	74.6%	3935	84.0%
B	Full Size Sedan	GVWR	4685	2517	2168	2479	98.5%	2163	99.8%	4642	99.1%
C	Luxury Sedan	LLVW	5655	2646	3086	2407	91.0%	2464	79.8%	4871	86.1%
C	Luxury Sedan	GVWR	5655	2646	3086	2530	95.6%	2921	94.7%	5451	96.4%
D	Minivan	LLVW	5250	2725	2725	2468	90.6%	1842	67.6%	4310	82.1%
D	Minivan	GVWR	5250	2725	2725	2578	94.6%	2662	97.7%	5240	99.8%
E	SUV	GVWR	5732	2712	3219	2541	93.7%	2998	93.1%	5539	96.6%
F, H & J	SUV	GVWR	5750	2800	2950	2793	99.8%	2920	99.0%	5713	99.4%
G & I	Compact SUV	LLVW	4165	2030	2155	1899	93.5%	1656	76.8%	3555	85.4%
G & I	Compact SUV	GVWR	4165	2030	2155	2018	99.4%	2147	99.6%	4165	100.0%

Appendix 7. TPMS Adapter Plate Assembly

A rubber hose threaded into the hole in the top of the adapter plate connected the plate to the tire's valve stem. Three extra-long stainless steel lug nuts replaced the normal nuts and connected the plate to the wheel. The plate and the hose connecting it to the valve stem rotate with the wheel. On the other side of the rotating air coupling (rotary union), a plastic hose connected the union to the pressure manifold inside the vehicle. The plastic hose was taped to the car to prevent it and the outside piece of the rotary union from rotating.



Appendix 8. Estimated Frequency of Tire Rotations and Replacements

	Average Vehicle Life (years)	Average Vehicle Life (miles)	Average Yearly Mileage (miles)
Passenger Cars	12.5	126,678	10134
Light Trucks	15.5	153,319	9892

	Passenger Cars		**Light Trucks**	
TPMS Reset	**Mileage**	**Action**	**Mileage**	**Action**
1	6000	Rotation	6000	Rotation
2	12000	Rotation	12000	Rotation
3	18000	Rotation	18000	Rotation
4	24000	Rotation	24000	Rotation
5	30000	Rotation	30000	Rotation
6	36000	Rotation	36000	Rotation
7*	45000	**Replacement**	45000	**Replacement**
8	51000	Rotation	51000	Rotation
9	57000	Rotation	57000	Rotation
10	63000	Rotation	63000	Rotation
11	70000	Rotation	70000	Rotation
12	76000	Rotation	76000	Rotation
13	82000	Rotation	82000	Rotation
14*	90000	**Replacement**	90000	**Replacement**
15	96000	Rotation	96000	Rotation
16	102000	Rotation	102000	Rotation
17	108000	Rotation	108000	Rotation
18	116000	Rotation	116000	Rotation
19	122000	Rotation	122000	Rotation
20			128000	Rotation
21*			135000	**Replacement**
22			141000	Rotation
23			147000	Rotation

*Pressure-sensor based systems may not need to be retrained after tire replacement if the wheels are returned to the original locations.